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entitled

Automated Eddy Current Analysis of Materials

by

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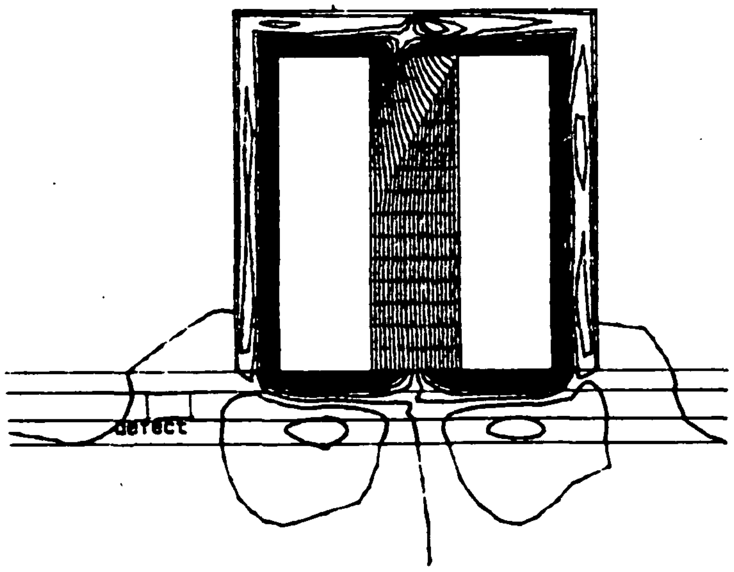
Principal Investigator



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1.0 INTRODUCTION

The nondestructive testing of aerospace components provides a challenging research activity for the evaluation of new technologies. Graphite based composites are becoming more accepted in critical structures which require a high strength-to-weight ratio. The primary disadvantages, at this time, are the lack of senstivity of most eddy current transducers and the inability to characterize a fabricated part as to its intended service capabilty; i.e. given known defect information, what will be the service life of the part? Attempts to answer these questions can be approached in two steps. First one needs to characterize defects in the material using some nondestructive evaluation technique and then be able to predict the service life of the component with the known defects. Metallic structures have traditionally been handled very well using NDE and fracture mechanics; however, there is still a lot of work to be done to be able to accomplish similar tasks with composite structures.

Since graphite is conducting to a small degree, i.e. the resistivity can vary anywhere from 500 to 1000 μΩ-cm, eddy current inspection techniques are applicable to determining certain flaws in graphite fiber based structures. Uniformity in resistivity in the normally manufactured products does currently present difficulties; however, it is anticipated that these can be overcome.

1.1 APPROACHES TO EDDY CURRENT SIGNAL INTERPRETATION

Although the use of expert systems to interpret eddy current signals is very new, concepts using feature extraction for defect identification have been around for awhile. The use of statistical pattern recognition, for example, has shown merit. An excellent paper on this technique is given in reference 1. Their work was concerned with characterizing flaws in austenitic steels used in power plant environments, which is a significantly different material from graphite fibers.

However, the analysis performed in that work does show the utility of feature abstraction and statistical techniques based upon signal characterization of known defect types. Some of these ideas are useful in developing knowledge based reasoning systems for defect characterization also.

This research effort has focused on the use of eddy current techniques for characterizing flaws in graphite-based filament-wound cylindrical structures. A major emphasis has also been placed upon incorporating artificial intelligence techniques into the signal analysis portion of the inspection process. Developing an eddy current scanning system using a commercial robot for inspecting graphite structures (and others) has been a goal in the overall concept and is essential for the final implementation for expert systems interpretation. Manual scans, as performed in the preliminary work here, do not provide sufficiently reproducible eddy current signatures to be easily built into a real time expert system.

The expert systems approach to eddy current signal analysis requires that a suitable knowledge base exist in which correct decisions as to the nature of a flaw can be performed. In eddy current, or any other expert systems used to analyze signals in real time in a production environment, it is important to simplify computational procedures as much as possible. For that reason, we have initially chosen to utilize the measured resistance and reactance values for the preliminary aspects of this work. A simple computation, such as phase angle of the signal, is certainly within the real time processing capability of the computer system. In the work described here, there has been a balance between physical measurements and finite-element calculations of those measurements. As described earlier, the goal is to evolve into the most cost-effective procedures for maintaining the correctness of the knowledge base.

1.2 Eddy Current Transducer Characterization

Another major activity performed in this work was to develop eddy current transducers specifically designed to inspect graphite fiber components. A number of relevant papers have been published in the last few years defining some of the problems in using eddy current probes to inspect components containing graphite[2-10]. The E-probes and horseshoe probes developed here provide large signals for both cut tows and impact damage. Major increases in the coupling efficiency with carbon fibers and in the sensitivity of flaw detection are desirable. The use of finite element models to predict eddy current signatures has also been a major focus of this work. Using the Ansoft Maxwell® software, values of the impedance changes for various defects are computed using both the E-probe and the horseshoe probe. It is anticipated that verification of this procedure as heuristic inputs into the expert system being developed for interpretation of the eddy current signals will be a continuing activity, however, logistically it is still more economical than preparing all possible flaws for signature characterization.

2.0 EXPERIMENTAL

Several filament wound graphite cylinders with prefabricated defects as shown in Figure 4 were prepared by MSFC contractors in M&P Laboratory. Eddy current scans are then able to produce a representative signal for this type of defect. The types of eddy current probes currently available at MSFC were normally pancake type probes, which are useful for finding surface and sub-surface cracks in metallic specimens. Initial measurments with the available probes indicated that very little coupling between the probe and the specimen was occurring. This observation motivated us to experiment with the finite element model to determine what was happening during the eddy current measurements.

The Ansoft Maxwell® software allows axisymmetric solution to electromagnetic fields in various geometries. The normal pencil probe used so often in eddy current does not work well with graphite fibers. Several factors are responsible for this ineffectiveness. Firstly, the overlap between the toroidal field emanating from the transducer is extremely small, resulting in a very small impedance change between air and the graphite fibers. Even with a number of fibers located parallel to each other in the filament wound cylinder do not provide sufficient coupling to differentiate between the resistivity changes in going from air to the graphite sample.

Two others types of probes were used in this work. E-probes and horseshoe probes were also used, with much better success. The E-probe can be modeled axis-symmetrically with the finite element programs so that a solution can be obtained. More importantly the electromagnetic field is unidirectional and in the proper orientation, providing excellent coupling with the fibers. The horseshoe probe is not axis-symetric, but it has been modeled as half of an E-probe. Experiments verifying that half an E-probe can model a horseshoe probe allows the use of defect signatures to be computed using the Maxwell® software. After some experimentation with the software, Mr. Wang was able to model horseshoe probes by placing the excitations coil axisymetrically and obtain solutions in that manner. At the time this report was written, only E-probe solutions were available; hence none of the horseshoe solutions are included within this report. There will be horsehoe probe solutions in reports for the second phase activities.

In order to verify the finite element model, several types of impedance plot were generated using the values of resistance and reactance calculated by the Ansoft software. For instance Table 1 shows the results from varying inspection frequency from 50 kilohertz to 5 megahertz and Figure 1 shows the corresponding impedance plane plot. This plot behaves normally, as would be expected from reference 2. Note that these calculations assume that the thickness of the material is much greater than the standard depth of penetration. Similar calculations of the materials points for ferrite and graphite. This result is shown in Figure 2. The normal display for such a plot is rotated 90° counter-clockwise. Again the results fit theory fairly well.

Samples of cylindrical components fabricated from resin 55A and fiber AS4-W-12K were provided by the Thiokol contractors, who work at the filament winding facilities in Building 4707. Eddy current measurements were obtained from these samples using standard pancake probes and the E-probe described below with the SmartEddy system and plotted according to Figure 3. The maximum specimen thickness available to us was only 0.168". Thus at the lower frequencies, the penetration was too deep for the impedance plot to go to 1. Otherwise the physical measurements fit the calculated data from Figure 1 very well.

The layout of defects embedded in the graphite samples is given in Figure 4. Two different thicknesses were provided, 0.168" and 0.085". Due to the low conductivity of the graphite, only the larger thickness was suitable for most of our measurements. The phase angle relationships expected between two different types of defects are shown in Figure 5. Note that the phase angles represent unique signatures for a particular type of defect and can be used to perform defect identification.

2.1 PROBE DESIGN CONSIDERATIONS

The design and fabrication of an eddy current transducer requires consideration for the following parameters:

1. Probe type
2. Inspection frequency
3. Optimum size
4. Cross-section of the winding area.
5. Optimum balance between wire size and number of turns

Very useful discussion of these parameters have been found in the work by Vernon[10], Dodd[15] and the Chalk River Training Manual[16]. For overall performance, the inspection frequency of the transducer plus cable must be less than the resonant frequency and the skin depth should be about 1.67 times the material thickness. The following calculations have been performed for the horseshoe probe designed in this research.

2.1.A. Probe Self-Inductance

Determination of the optimal operating frequency for the eddy current inspection of graphite fiber components is assisted by knowing the actual impedance as seen by the alternating current generator for the test. in general, the operating frequency of the inspection transducer should be around 20% of the resonance frequency. In order to come up with this information, we were able to calculate the self-inductance using Ampere's Law and then measure it for confirmation. Our transducers are not round or cylindrical as normally considered in such calculations, so there was some question about possible errors in the calculation. Being able to measure the inductance of the final assembly was beneficial. Capacitance of the transducer-cable arrangement is even more difficult; however, we were able to measure that parameter also.

The typical values for our transducers are given by:

$L = 4 \pi k_m N^2 A * 10^{-10} / l$ $\qquad$ k_m = geometrical factor = 3

$= 4*3.1416*3*7^2*80.6*10^{-10} /5.1$

$= 2.92$ microhenrys

Capacitance (measured) = 87.6 picofarads = $8.7 * 10^{-11}$ farads

Note that the measured value for self inductance was determined to be 3.35 microhenrys or 3.35 * 10^{-6} henrys which turned out to be reasonably close to the calculated value. That value is then used to determine the resonance frequency, which is given by:

$$f_r = 1/2\pi\sqrt{LC}$$

$$= \frac{1}{2*3.1416*\sqrt{3.35 *10^{-6}*8.76*10^{-11}}}$$

$$= 9.3 \text{ Mhz}$$

Inspection frequencies up to 2 Mhz would then be acceptable for these transducers.

2.1.B. Calculation of Depth of Penetration for Graphite Fiber Components.

The empirical relationship between resistivity and frequency derived by Vernon[10] for eddy current cup probes gives:

$$\rho = \frac{195.6*10^{-6} * r^2 * f}{(\tan \theta_L + 0.158)^2}$$

$$= 17303 \ \mu\Omega\text{-cm}$$

when f = 4 Mhz, $\theta_L = 60^\circ$ and r = 0.125 mm.

For 2 Mhz excitation, the depth of penetration would then be

$$\delta = 1.98 \sqrt{\rho/f} \quad = 1.98 \sqrt{17300/2*10^6}$$

= 0.18 inches

For thinner samples, higher frequencies are required and redesign of the probe to have higher resonance frequency will have to be done. Since our transducers are not cup probes, some of these calculations may require correction, although to date excellent correlation has been obtained.

Based upon these calculations we wound our own eddy current E- and horseshoe probes using 7 turns of wire. The E-probe transducer was constructed using transformer cores supplied by Magnetics. Unfortunately we were not given the magnetic permeability of the material. A major diasdvantage of the E-probe is that two signals are normally obtained since there are actually two different EM fields. This means that the expert system analyzing the signals has to account for both signals. With this analysis requirement in mind, a horseshoe probe was fabricated to generate only one signal for each change in impedance occuring in scanning the part.

In order to fabricate our own horseshoe probe, an E-probe was cut in half and reassembled as a horseshoe probe, using 7 turns of wire again. The signal obtained from scanning the samples should theoretically be identical to just one of the lobes of the E-probe. However the coupling efficiency is proportional to the footprint (area) of the transducer and the horseshoe probe is about 80% the area of half of the E-probe. Hence the coupling efficiency is not quite as good and correspondingly smaller signals are obtained.

3.0 RESULTS

Signals obtained by scanning the graphite samples fabricated at MSFC are presented in

Figures 6 - 10. These data were obtained using the SmartEddy for the data acquisition. The SmartEddy system provides decomposition into resistance and reactance for the time aplitude plots. Both impedance plane plots and amplitude displays of resistance and reactance are shown here. Impedance plane displays of the signals can be more informative in that the phase angle changes which occur for a given defect are consistant with the type of defect and the defect depth. However for the purposes of the expert system analysis, we are still trying to determine if reactance and resistance changes can be used for interpretation of the data.

Two major points need to be discussed here. Firstly, the resistivity of graphite fibers are not consistent throughout the sample. Hence the materials point keeps changing throughout a scan. This will have to be taken care of during the expert system analysis. Secondly, the theory and most eddy current specialists don't believe that eddy currents can provide an indication of delaminations. Our samples were fabricated using a graphite knot for a delamination (See Figures 4 and 6) and we were able to observe the embedded delamination (although the signal was small). A kissing debond, which is obviously more difficult to fabricate would not have given such an obvious indication of a defect. We currently feel that we were able to see a volume change since the delamination was caused by inserting a dielectric material between two graphite layers.

An ultrasonic C-scan of the sample was also taken in order to compare to the eddy current data. Note that the delamination is quite evident in the through transmission scan. The other defects are easily distinguished and there is a lot of noise in the image. The eddy current image of this specimen would be much more useful once all systems are available for use.

3.1 FINITE ELEMENT MODELING

The Ansoft software Maxwell® was used to compute the interaction between the various eddy current transducers and the materials. The program allows one to generate a three dimensional model and solve for the electromagnetic fields in an axisymmetric environment. A schematic of the user interface to the program is shown in Figure 12. Mr. Morgan Wang was the student who performed the finite element modeling with this software. The results can only be displayed in two dimensions. However modules were developed for simulation of scans across a particulare defect. For instance, Figures 13 and 14 show simulated values for resistance and reactance when displaced from the defect and when sitting over the defect for two different flaws. Note that the changes are small, nonetheless they are observable.

It is anticipated that for the final expert system implementation, a series of these calculations would provide the simulated time varying amplitude impedance of the eddy current transducer moving over the defect. This feature would then be added to the knowledge base to provide predictive capability for that type of flaw.

3.2 EXPERT SYSTEMS APPROACH TO EDDY CURRENT SIGNAL ANALYSIS

The goal in using an expert system for interpretation of eddy current signals relies upon the use of heuristics and efficient strategies for sorting through the decision trees in identifying the type to defect being observed. If these goals can be satisfied, then the arduous computation required for statistical pattern recognition can be reserved for the difficult interpretations and the envisioned expert system can handle the real time inspection requirements.

To demonstrate the foundation upon which statistical interpretations are based, it is interesting to reconsider the procedures described in Reference 1. Figure 15 shows an example of the type of eddy current signals obtained from edm notches on the austenitic samples and the corresponding features extracted from the signals. A more definitive display of the geometric and computational aspects of the features are given in Figure 16, which shows how geometry of the time varying features can be uniquely ascribed to a particular defect. Note the heavy computational requirements for this type of analysis.

In considering an alternative methodology, Figure 17 displays the expert systems model planned here. There are several features contained in this concept which are significant. In the DATA INPUT section, note that the use of a robotic scanning system will enable consistent time-varying amplitudes to be obtained. Manual scanning, as has been performed in this phase of the work, does not provide consistent results. The implementation is being performed in several phases as instrumentation becomes available. An anticipated application of neural networks is obvious to the defect identification problems in eddy current inspection[11]. The build-up of the knowledge base is also occurring in stages using finite element models and fabricated defects to generate decision criteria for the expert system. The only other work reported previously dealt with metallic components and primarily developed a heuristic for deteriming crack depths and widths[12-13].

Inputs into the knowledge base are defined by calibrated defects and finite element models. We anticipate that finite element modeling, once complete verification that the models are as good in predicitng impedance changes as real defects, will be much more economical and faster methodolgy for construction of the knowledge base.

The MacIvory® computer was chosen for the expert system platform, providing both user friendly interfaces and symbolic processing. The interface between the Symbolics engine and the MacIntosh® is the RPC Interface. RPC stands for Remote Procedural Call, i. e. the two processors operate independently of each other and provide remote calls to the other processor to handle a particular function which can only be handled by the processor. Lisp is the language used by the MacIvory and Genera is the operating environment. Of course the MacIntosh environment is standard to that computer system. Evaluation of this platform will obviously be more strenous in the second phase.

Mr. Sung Lee has been the graduate student working with the artificail intelligence part of the task. In his first few months working on the project, he has developed programs and interfaces to call up edddy current data, plot several types of plots (i.e. emulate the SmartEddy to a degree) and perform some smoothing routines. Examples of these displays are given in Figures 19-21. Due to the nature of the manually scanned data obtained from early measurements of the test specimens, he was not able to uniquely characterize the signals from the defects. Once the robot scanning system is in place, that task will become more easily accomplished. A major effort will be needed to overcome the variable resistivity problem; however, we currently feel that a neural network on the fron end of the data-acquisiton will be very beneficial. That is also a task to be resolved in the second phase.

4.0 CONCLUSIONS

This work has resulted in the development of eddy current transducers for the inspection of carbon filament materials with improved sensitivity and the development of preliminary software modules for the interpretation of eddy current signals. Improved coupling efficiencies achieved with the E-probes and horseshoe probes are exceptional for graphite fibers[14-15]. The eddy current supervisory system and expert system are being developed on a MacIvory® system. Since the robot scanning system was not available during this phase of the research, only the basic foundations for the ai was laid. Proof of the concept will be performed in the next phase. Utilization of finite element models for pre-determining eddy current signals has been shown to be useful in this work, both for understanding how electromagnetic fields interact with graphite fibers, but also for use in determining how to develop the knowledge base.

The Appendicies attached to this report contain the software currently developed to display the eddy current signals on both the IBM PC (SmartEddy type instrument) and the MacIvory Workstation. This software also shows the intent towards user-friendly displays for ease-of-use. This pattern will continue.

5.0 ACKNOWLEDGEMENTS

This work has been benefitted by a number of helpful discussions with several researchers in the field including Ms. Susan Vernon and Jeffrey Warren of the Naval Surface Weapons Laboratory, Brian Lempriere of Boeing Aerospace, and Ken Woodis, Lisa Hediger, and Craig Bryson at the NDE Laboratory at MSFC. Also we are indebted to R. Holmes, Wendell De Weese and the Thiokiol filament winding group for preparing our specimens and to Magnetics Corporation for the ferrite samples. Gratitude is also expressed to the students who worked on this project, Morgan Wang and Sung Lee.

BIBLIOGRAPHY

1. Doctor, P. G., et al., "Pattern Recognition in Methods for Characterizing and Sizing Flaws Using Eddy Current Data", in *Eddy Current Characterization of Materials and Structures*, ASTM STP 722, (1981) pp 461-483.

2. Vernon, S.N., "The Universal Impedance Diagram of the Ferrite Pot Core Eddy Current Transducer", *IEEE Transactions on Magnetics*, **25** (1989) pp 2639-2645.

3. Sabbagh, H.A. and S.N. Vernon, "Description and Verification of of a model of Eddy current Probes with Ferrite Cores", *Review of Progress in Quantitative NDE*, **3A** (1984), Plenum Press, New York, pp 653-662.

4. Vernon, S. N., "Parametric Eddy Current Defect Depth Model and its Application to Graphite Epoxy", *NDT International*, **22** (1989) pp 139-148.

5. Gammell, P.M. and S. N. Vernon, "Eddy Current Inspection of Broken Fiber Flaws in Non-metallic Fiber Composites", *Review of Progress in Quantitative NDE*, **4** (1985) pp 1229-1237.

6. Vernon, S. N., "Probe Properties Affecting the Eddy Current NDI of Graphite Epoxy", *Review of Progress in Quantitative NDE* **7** (1987) pp 1113-1123.

7. Vernon, S.N., "Eddy urrent Inspection of Thick Carbon Fiber Reinforced Composites", *Review of Progress in Quantitative NDE* **8** (1988) pp 1543-1550.

8. Bowler, J.R., "Electromagnetic Fields in Advanced Composites" pp 736-741.

9. Valleau, A. R., "Eddy Current Nondestructive Testing of Graphite Composite Materials", *Materials Evaluation*, **48** (1990) pp 230-239

10. Vernon, S. " A Single-sided Eddy-current Method to Measure Electrical Resistivity", *Materials Evaluation*, **46** (1988) pp 1581-1587

11. Udpa, L. and S.S. Upda, "Eddy Current Defect Characterization Using Neural Networks", *Materials Evaluation*, **48** (1990) pp 342 - 347.

12. Udpa, L. and W. Lord, "A Search-based Imaging Sysem for Electromagnetic Nondesructive Testing", *IEEE Expert* **4**, (1989) 18-26

13. Udpa, L. and W. Lord, "An AI Approach to the Eddy Current Defect Characterization Problem", *Review of Progress in Quantitative NDE*, **8** (1988) pp 899-906.

14. Shull, P. J., T. EE. Capobianca, amd J. C. Moulder, "Design and Characterization

of Uniform Field Eddy Current Probes", *Review of Progress in Quantitative NDE*, **6A** (1986) pp 695 - 703.

15. Dodd, C. V., and W. E. Deeds, "Absolute Eddy Current Measurements of electrical Conductivity", *Review of Progress in Quantitative NDE*, **2**, 1982, pp387-393 Plenum Press, New York

16. Cecco, V. S., G. Van Drunen, and F. L. Sharp, "Eddy current Manual, Volume 1", Chalk River Laboratories, Chalk River, Ontario

FIGURES 1 - 21

TABLE 1. NORMALIZED EDDY CURRENT SIGNALS FOR GRAPHITE FIBER USING ANSOFT MAXWELL® FINITE ELEMENT MODEL

FREQUENCY (Hz)	RESISTANCE	REACTANCE
50 k	0.099	0.996
100 k	0.152	0.942
200 k	0.18	0.882
500 k	0.21	0.790
800 k	0.225	0.730
1 M	0.23	0.670
1.5 M	0.214	0.570
2 M	0.214	0.570
2.5 M	0.197	0.530
3 M	0.179	0.498
3.5 M	0.158	0.469
4 M	0.135	0.445
5 M	0.026	0.342

FIGURE 1. NORMALIZED IMPEDANCE PLANE DIAGRAM FOR GRAPHITE FIBERS

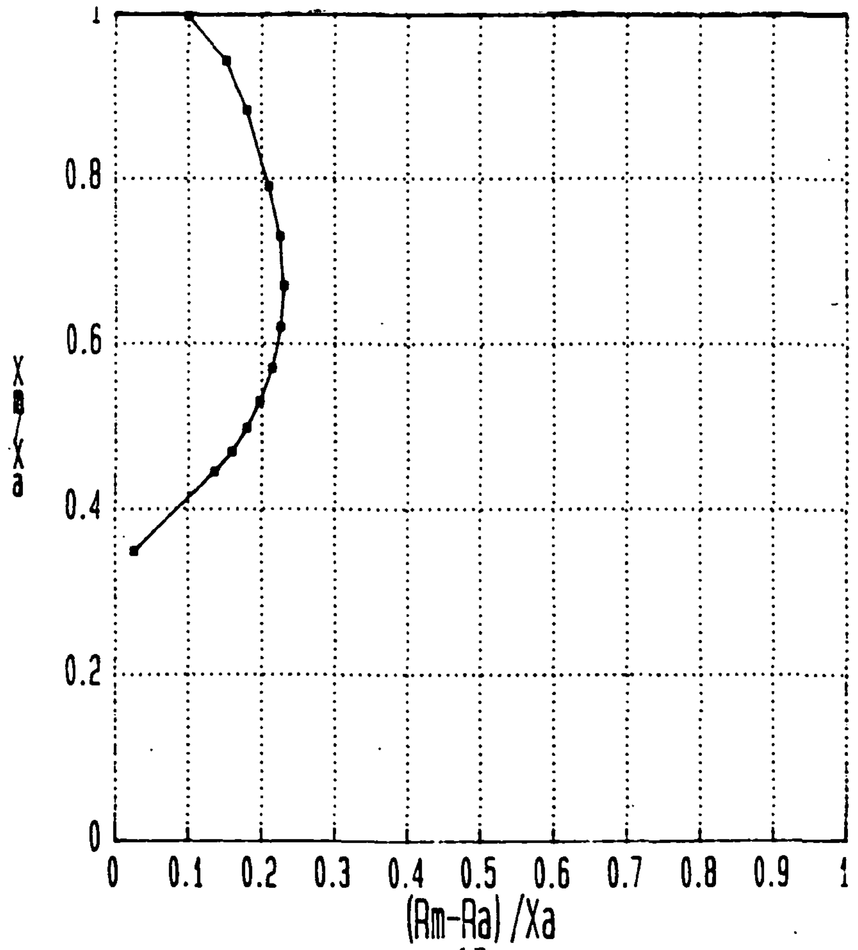


FIGURE 2. CALCULATED MATERIALS POINTS FOR GRAPHITE EPOXY AND FERRITE

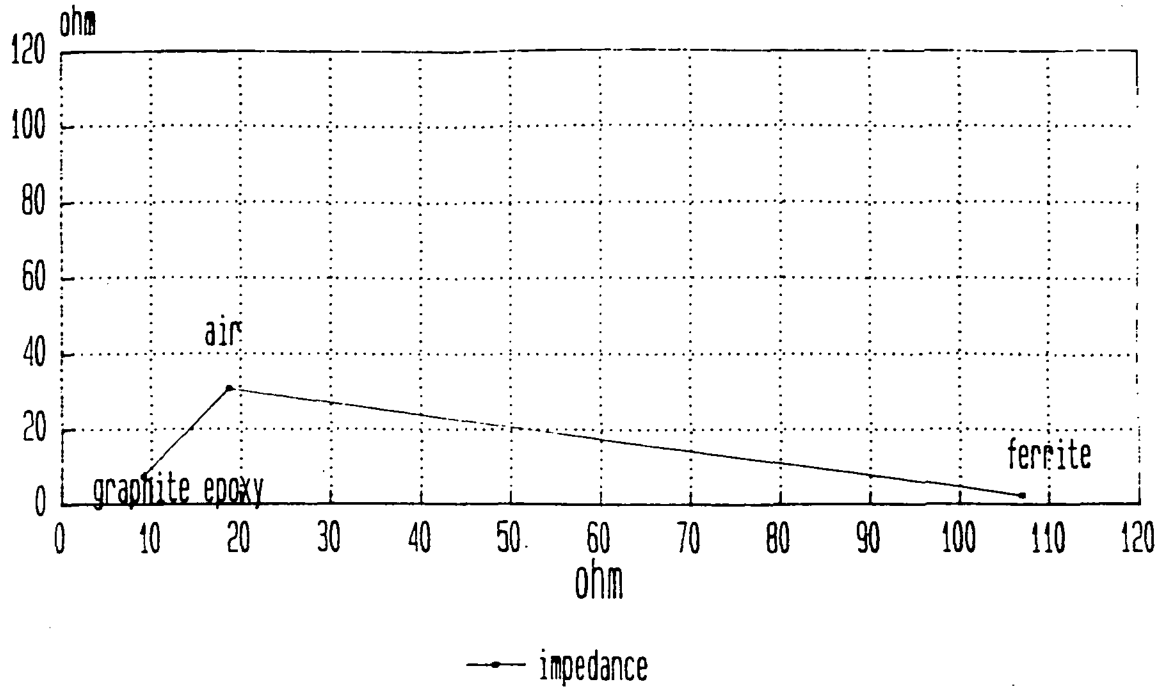


FIGURE 3. IMPEDANCE PLANE DIAGRAM OF EDDY CURRENT MEASUREMENTS ON GRAPHITE FIBER SAMPLE

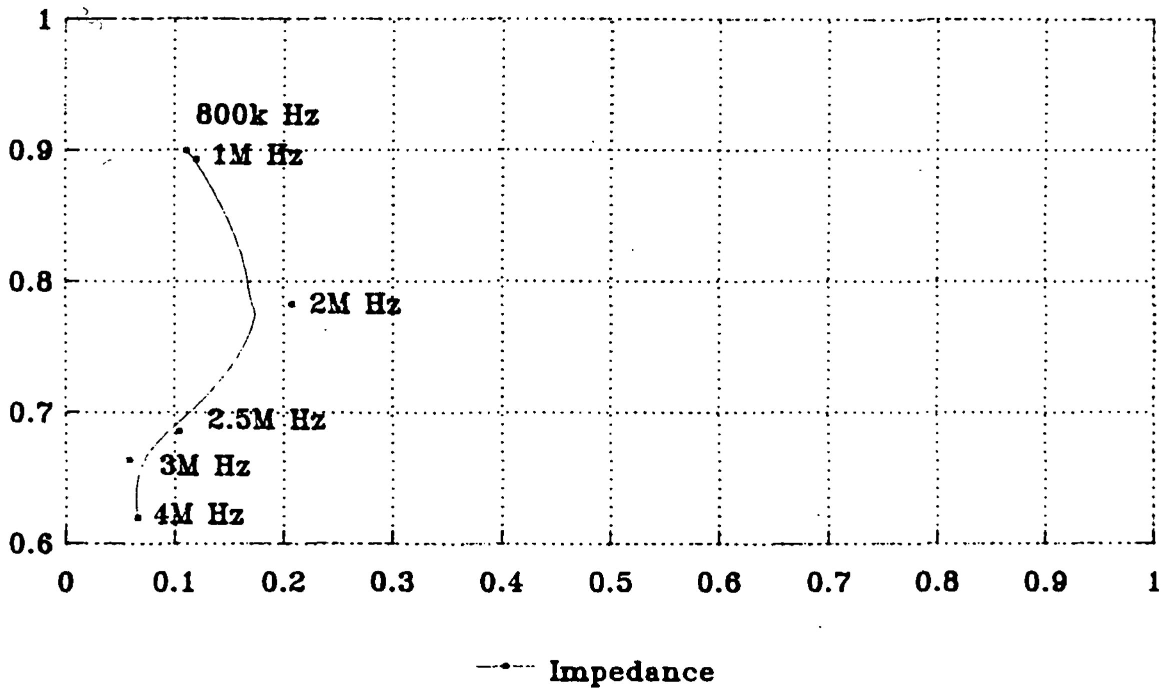


FIGURE 4. GRAPHITE EPOXY TEST CYLINDER 0.168 INCHES THICK

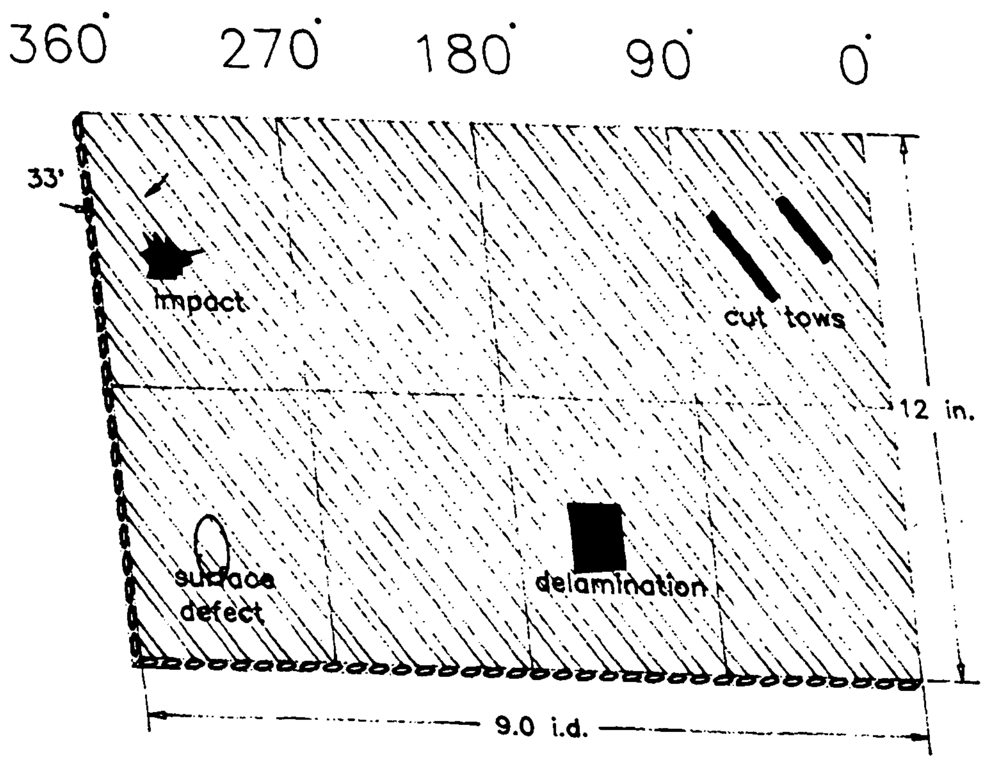


FIGURE 5. PHASE ANGLE RELATIONSHIPS FOR DEFECTS IN GRAPHITE FIBER MATERIAL

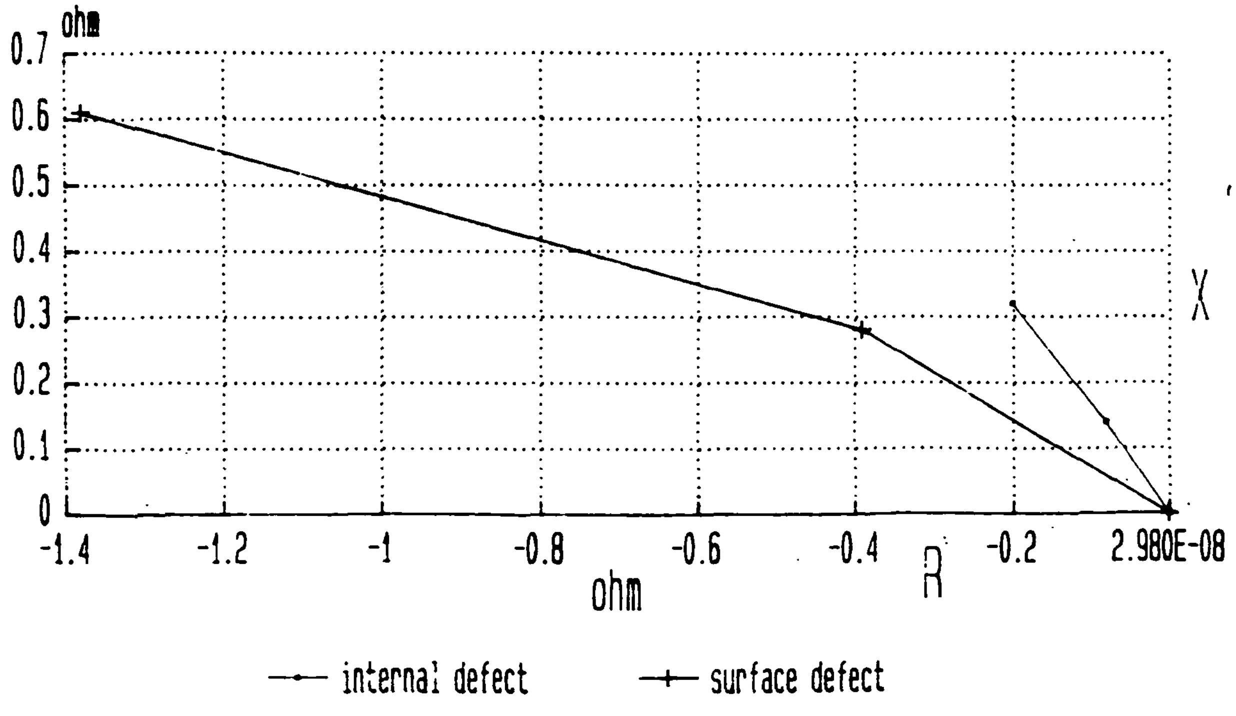
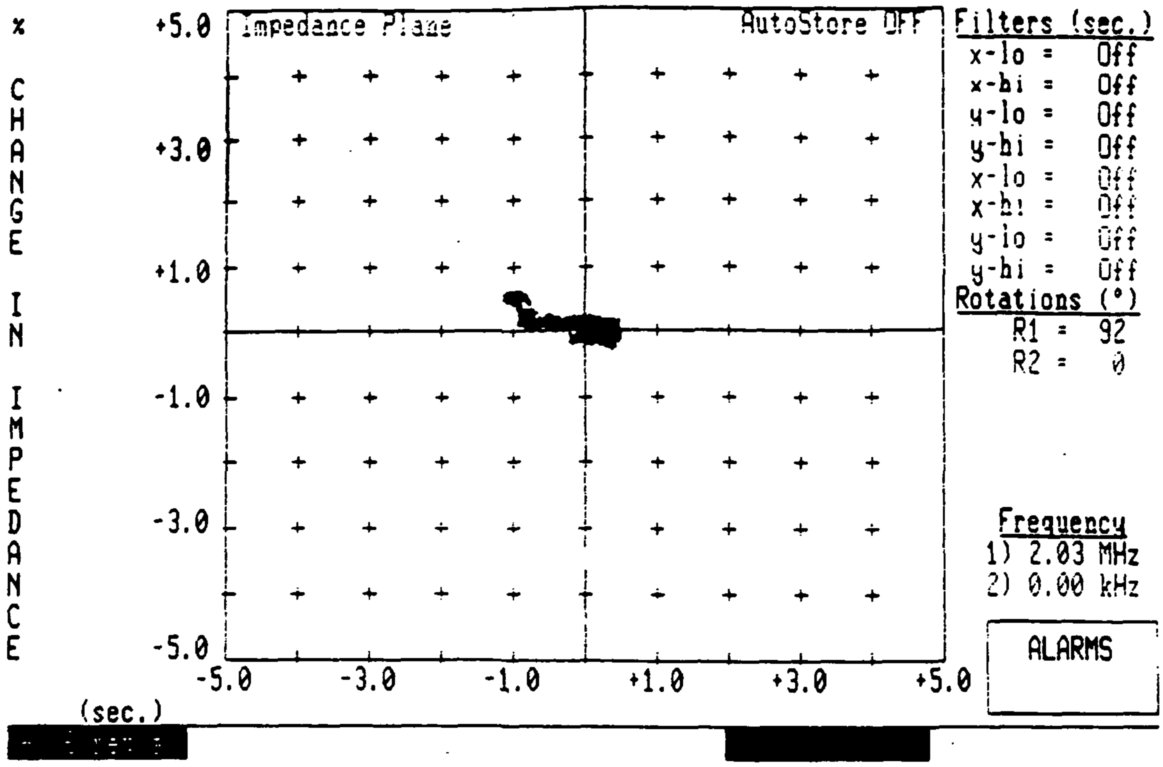


FIGURE 6. SMARTEDDY DISPLAYS OF DELAMINATION IN TEST SAMPLE



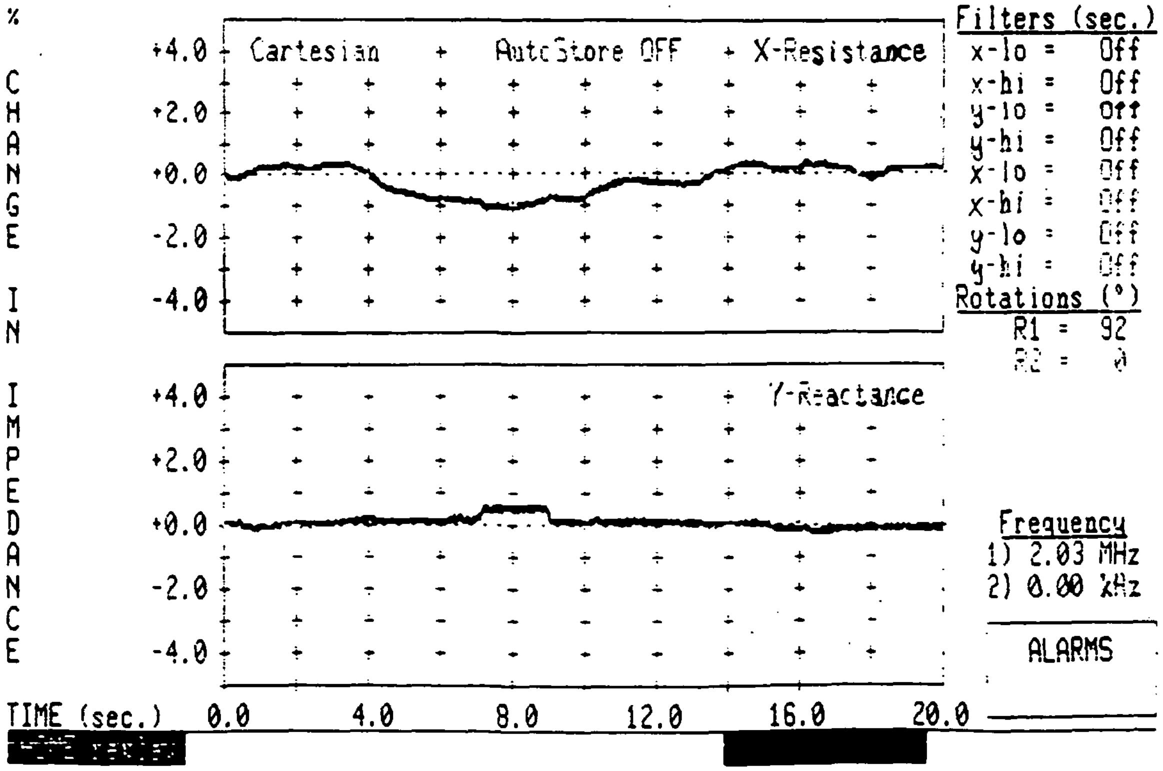
Filters (sec.)

x-lo =	Off
x-hi =	Off
y-lo =	Off
y-hi =	Off
x-lo =	Off
x-hi =	Off
y-lo =	Off
y-hi =	Off

Rotations (°)

R1 =	92
R2 =	0

Frequency
1) 2.03 MHz
2) 0.00 kHz



Filters (sec.)

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x-hi =	Off
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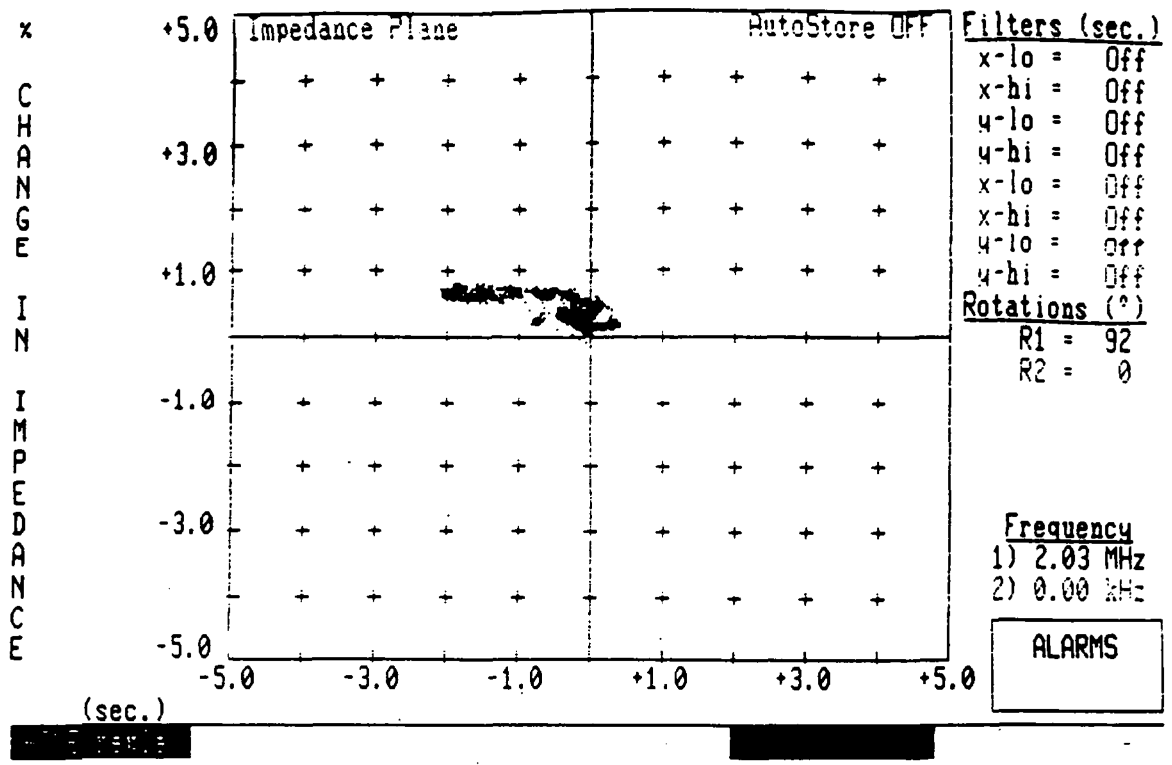
x-hi =	Off
y-lo =	Off
y-hi =	Off

Rotations (°)

R1 =	92
R2 =	0

Frequency
1) 2.03 MHz
2) 0.00 kHz

FIGURE 7. SMARTEDDY DISPLAYS OF NEAR SURFACE INTERNAL DEFECT IN TEST SAMPLE USING GRAPHITE KNOT



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x-lo = Off
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Rotations (°)
R1 = 92
R2 = 0

Frequency
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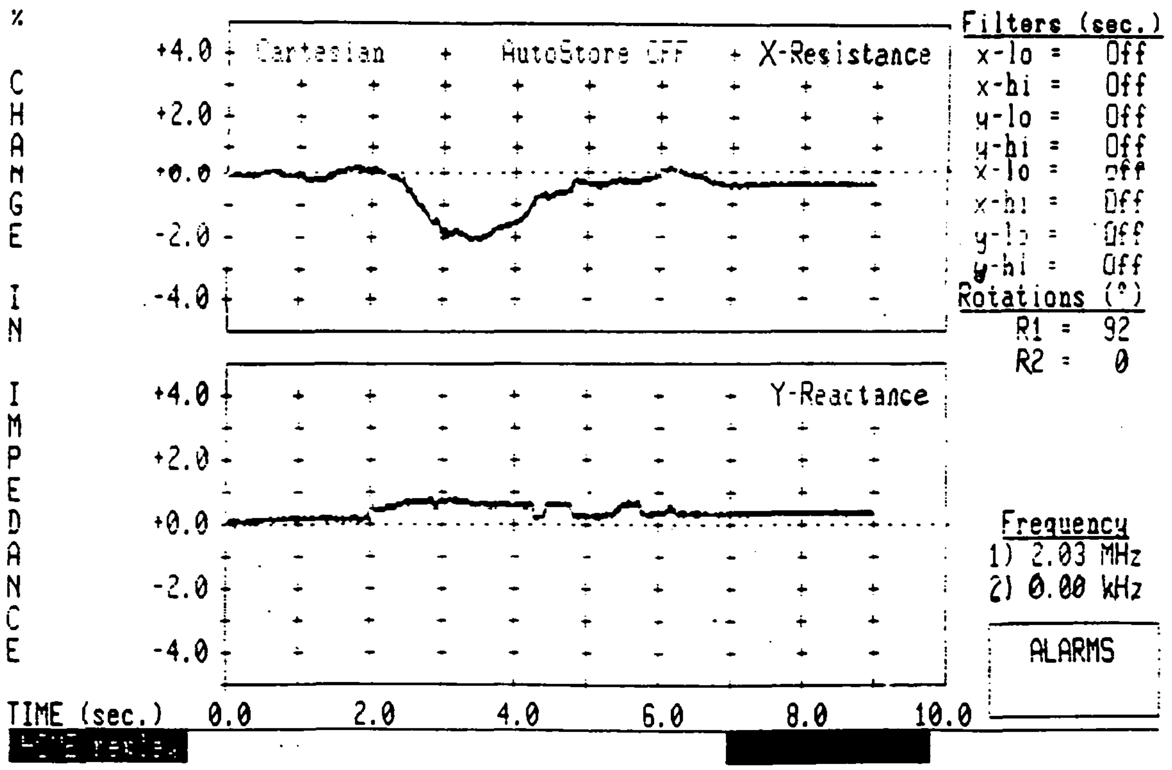
2) 0.00 kHz



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Rotations (°)
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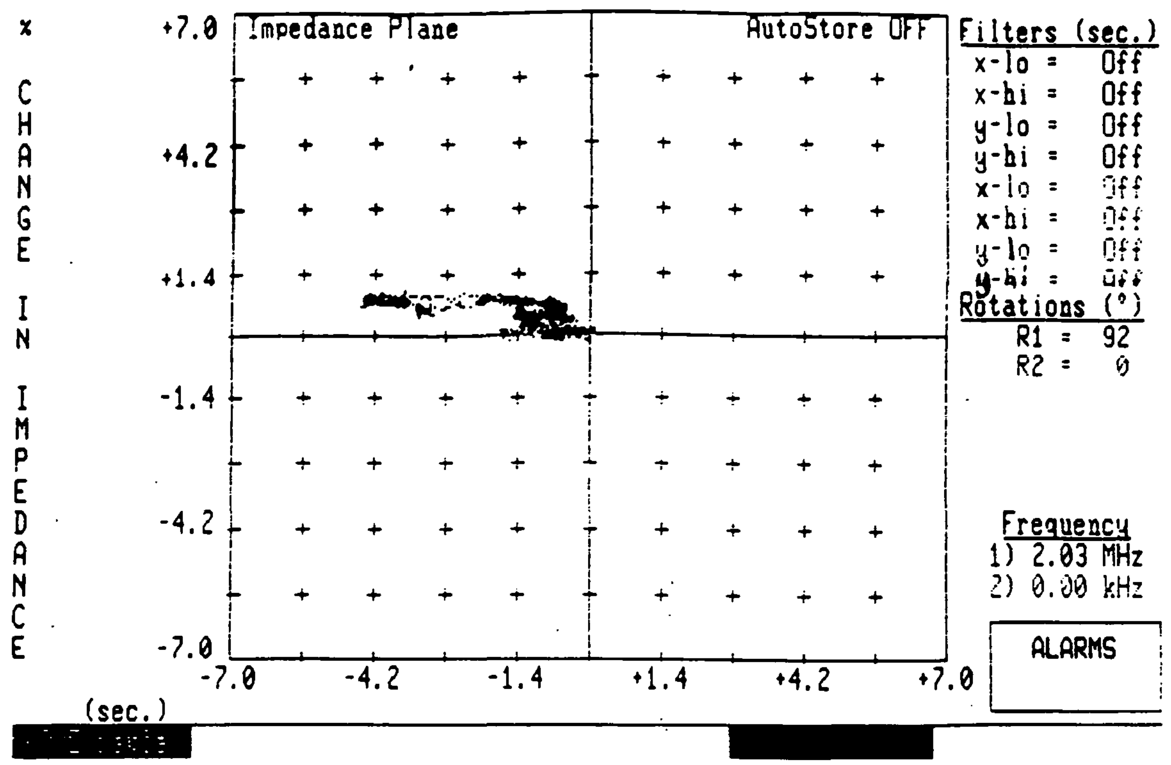
R2 = 0

Frequency
1) 2.03 MHz
2) 0.00 kHz

FIGURE 8. SMARTEDDY DISPLAYS OF SURFACE DEFECT IN TEST SAMPLE USING GRAPHITE KNOT.



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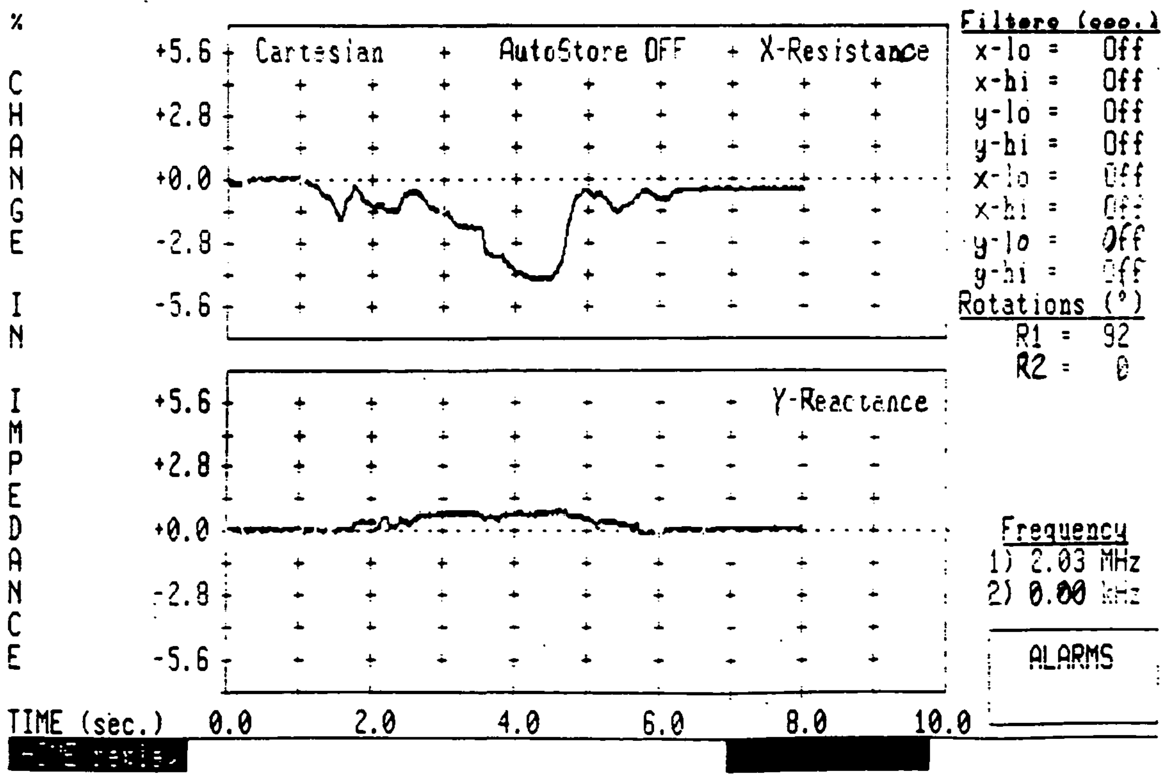
y-hi = Off
Rotations (°)
R1 = 92
R2 = 0

Frequency
1) 2.03 MHz
2) 0.00 kHz



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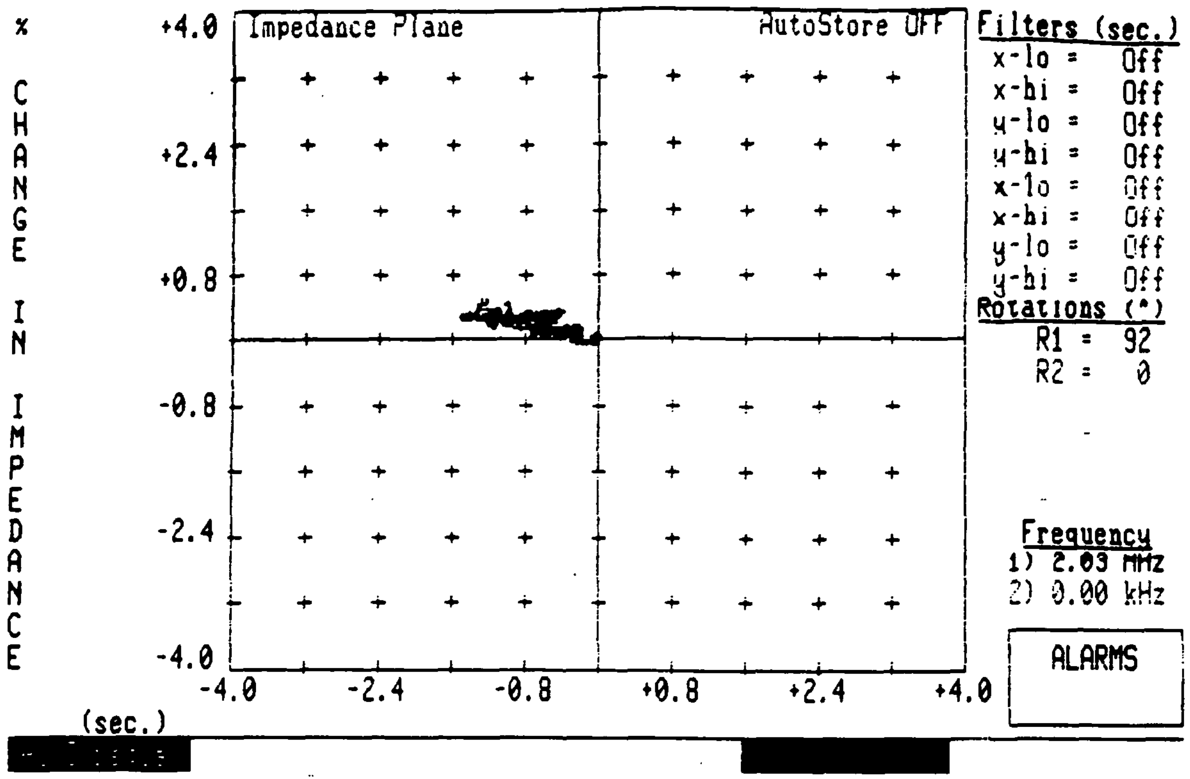
y-hi = Off
Rotations (°)
R1 = 92
R2 = 0

Frequency
1) 2.03 MHz
2) 0.00 kHz

FIGURE 9. SMARTEDDY DISPLAYS OF IMPACT DAMAGE IN TEST SAMPLE



Filters (sec.)
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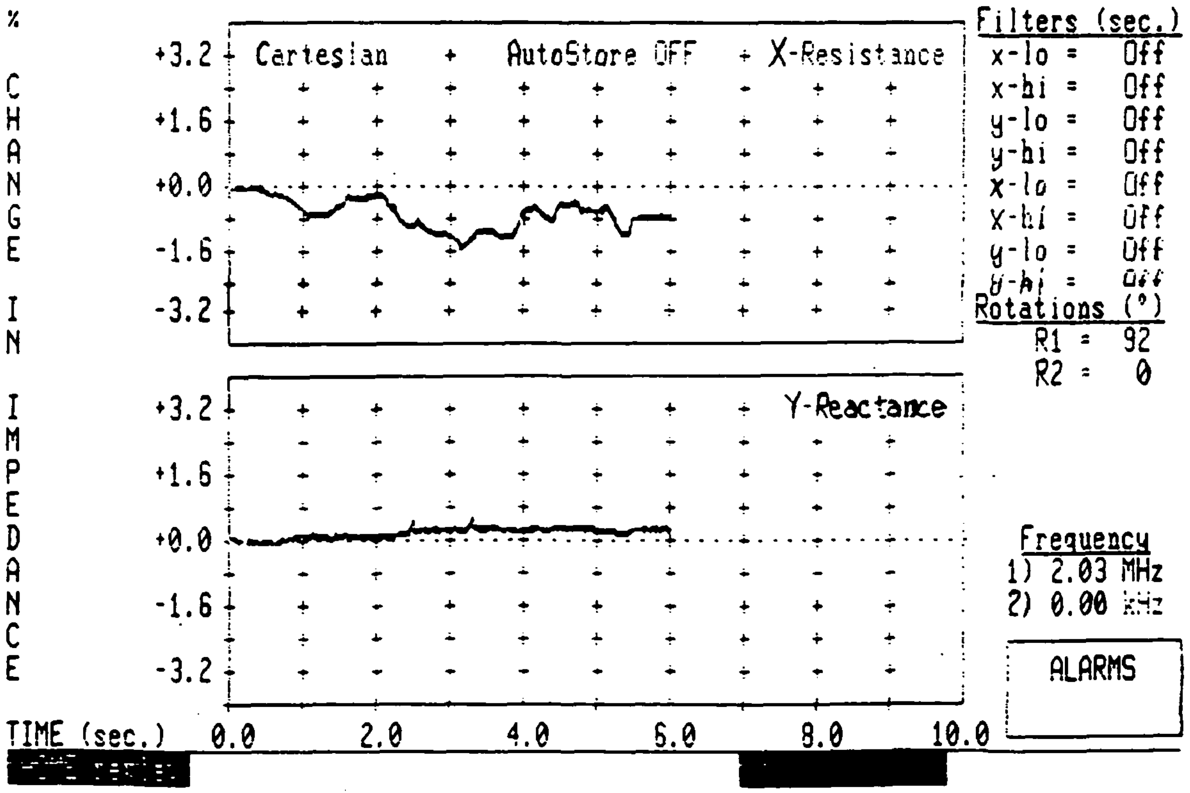
x-hi = Off
y-lo = Off
y-hi = Off
x-lo = Off
x-hi = Off
y-lo = Off
y-hi = Off
Rotations (°)
R1 = 92
R2 = 0

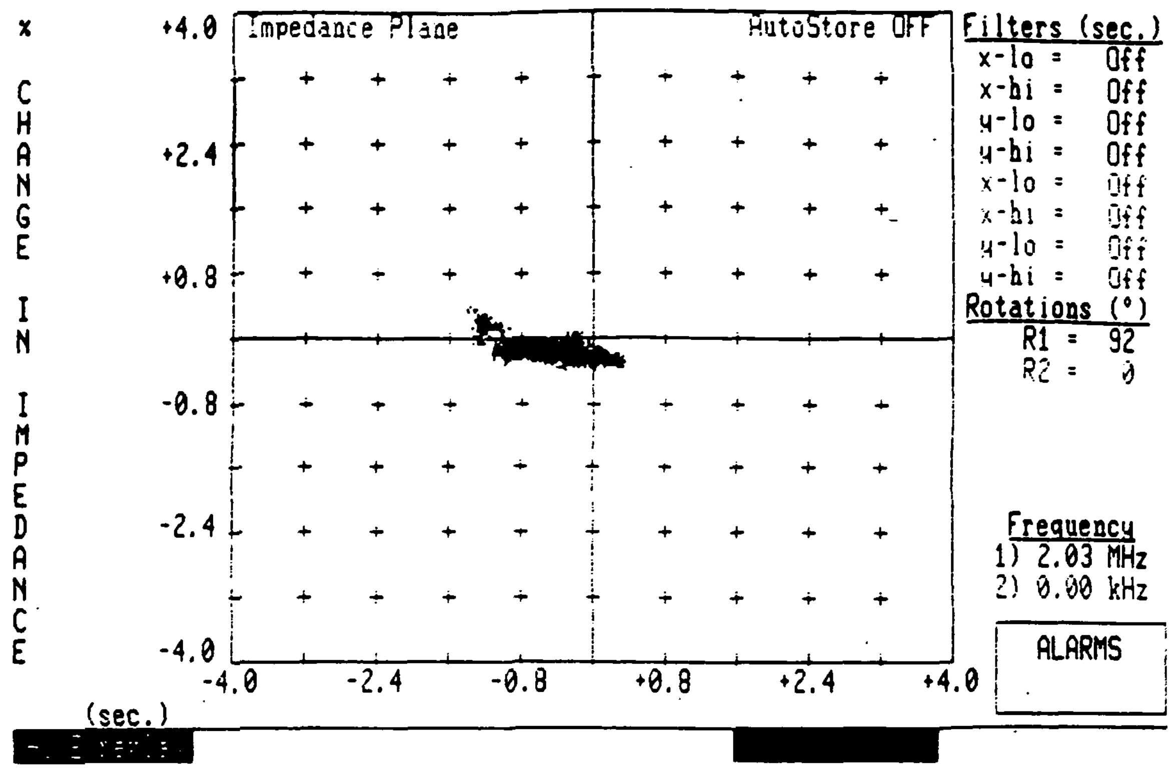
Frequency
1) 2.03 MHz
2) 0.00 kHz



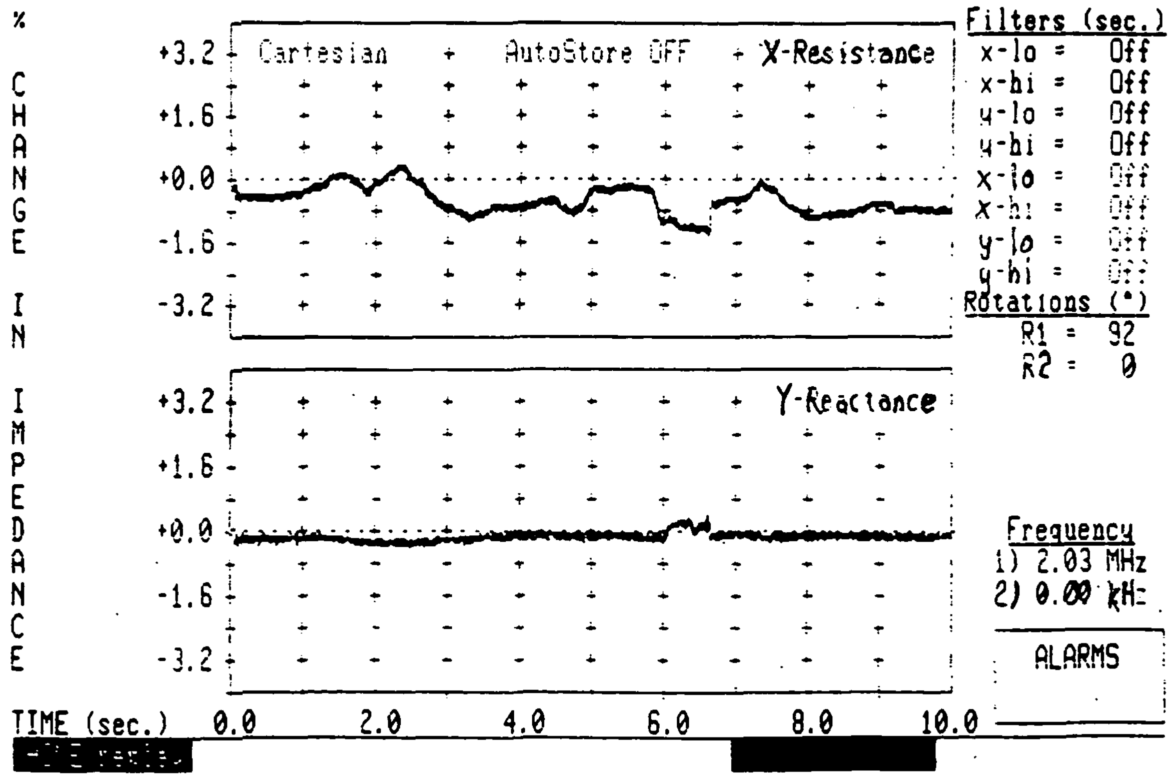
Filters (sec.)
x-lo = Off
x-hi = Off
y-lo = Off
y-hi = Off
x-lo = Off
x-hi = Off
y-lo = Off
y-hi = Off
Rotations (°)
R1 = 92
R2 = 0

Frequency
1) 2.03 MHz
2) 0.00 kHz

FIGURE 10. SMARTEDDY DISPLAYS OF INTERNAL CUT TOWS IN TEST SAMPLE

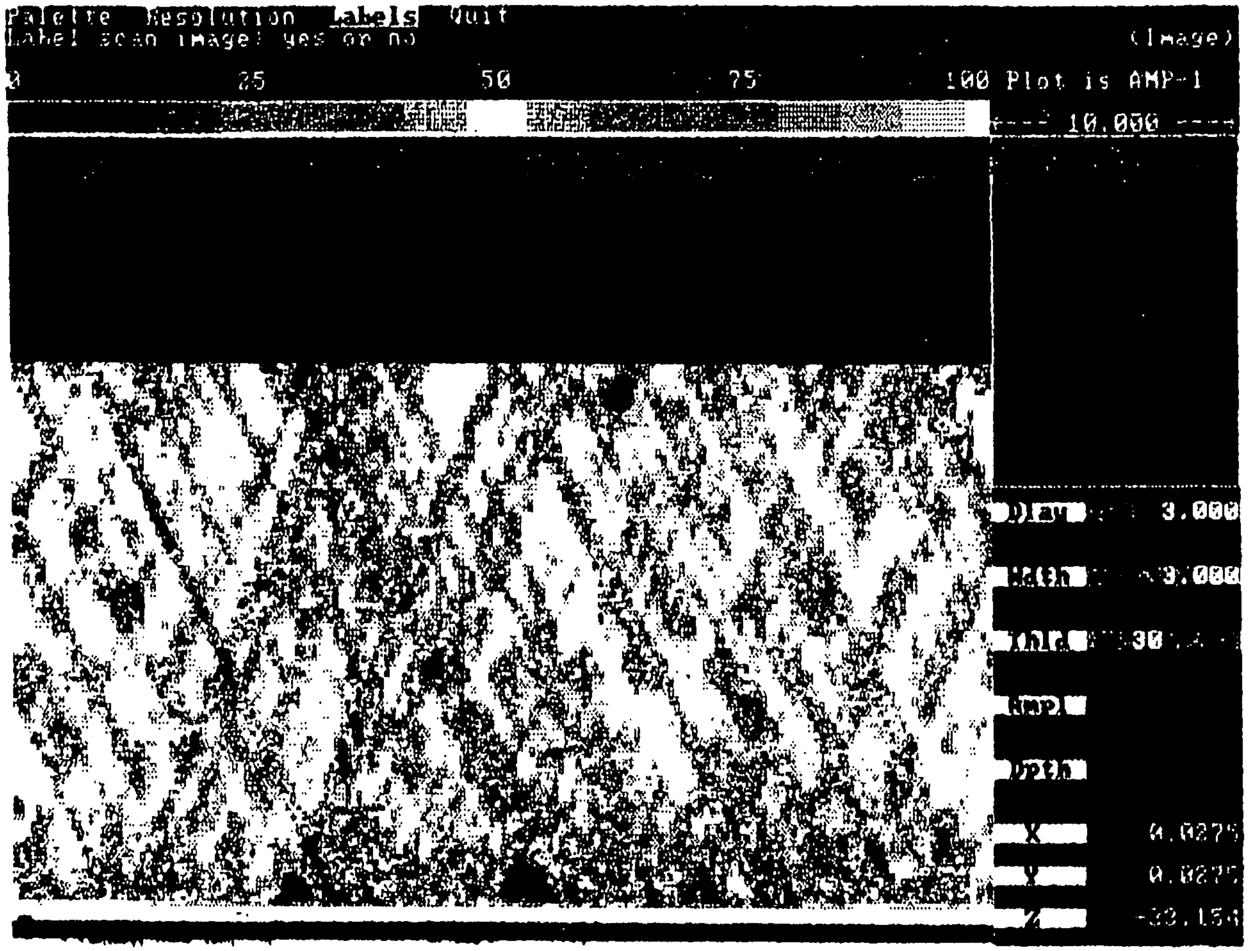


Filters (sec.)
x-lo = Off
x-hi = Off
y-lo = Off
y-hi = Off
x-lo = Off
x-hi = Off
y-lo = Off
y-hi = Off
Rotations (°)
R1 = 92
R2 = 0
Frequency
1) 2.03 MHz
2) 0.00 kHz



Filters (sec.)
x-lo = Off
x-hi = Off
y-lo = Off
y-hi = Off
x-lo = Off
x-hi = Off
y-lo = Off
y-hi = Off
Rotations (°)
R1 = 92
R2 = 0
Frequency
1) 2.03 MHz
2) 0.00 kHz

FIGURE 11. ULTRASONIC C-SCAN DISPLAY OF GRAPHITE FILAMENT WOUND CYLINDER


Palette Resolution Labels Quit
Label scan image! yes or no
(Image)
0 25 50 75 100 Plot is AMP-1
10.000
3.000
3.000
30
X 0.0275
Y 0.0275
Z -33.154

NOTE THAT IN COMPARISON WITH FIGURE 4, ONLY THE DELAMINATION DEFECT IS EASILY OBSERVED.

FIGURE 12.
ELECTROMAGNETIC FIELD SOLVER

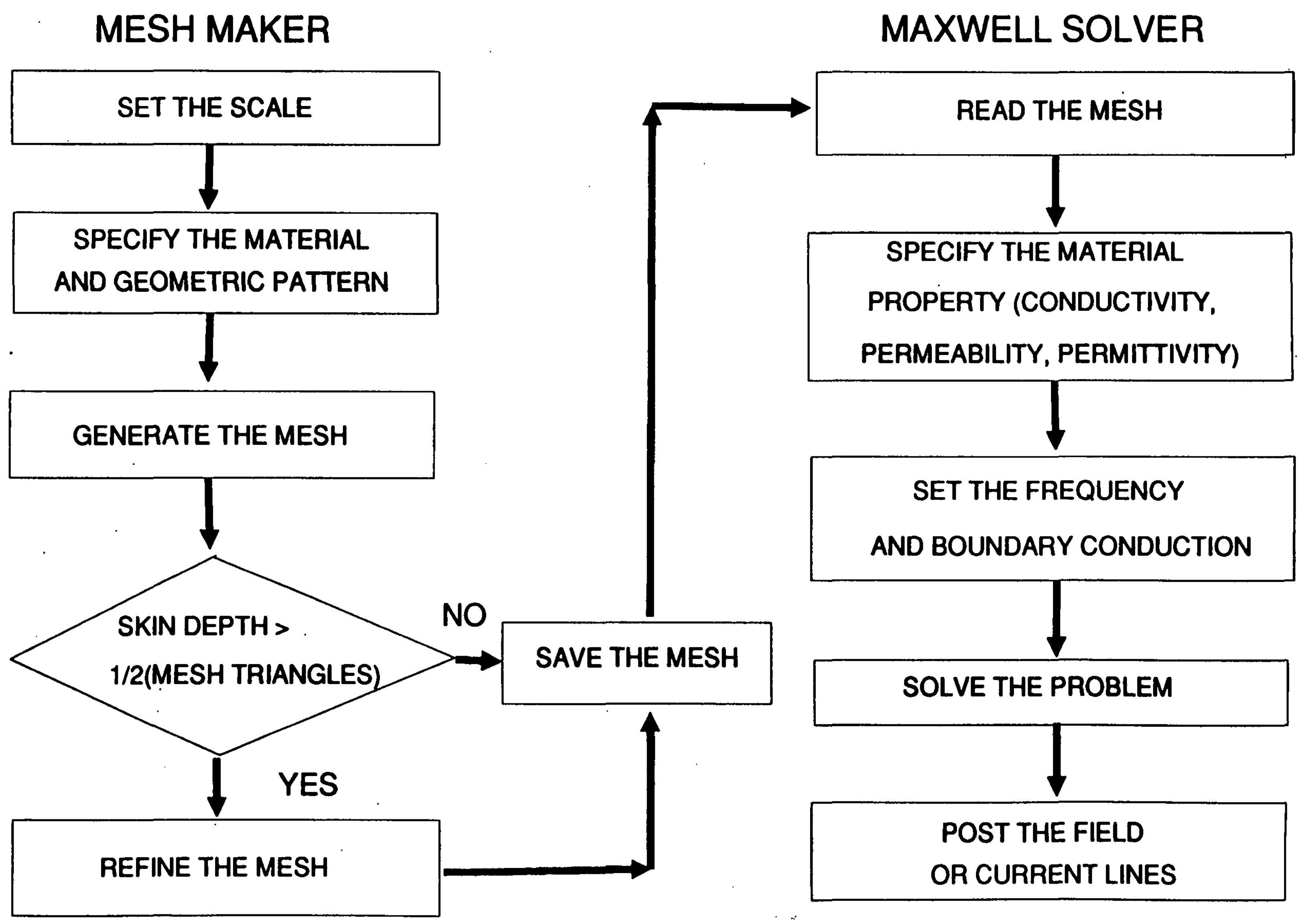
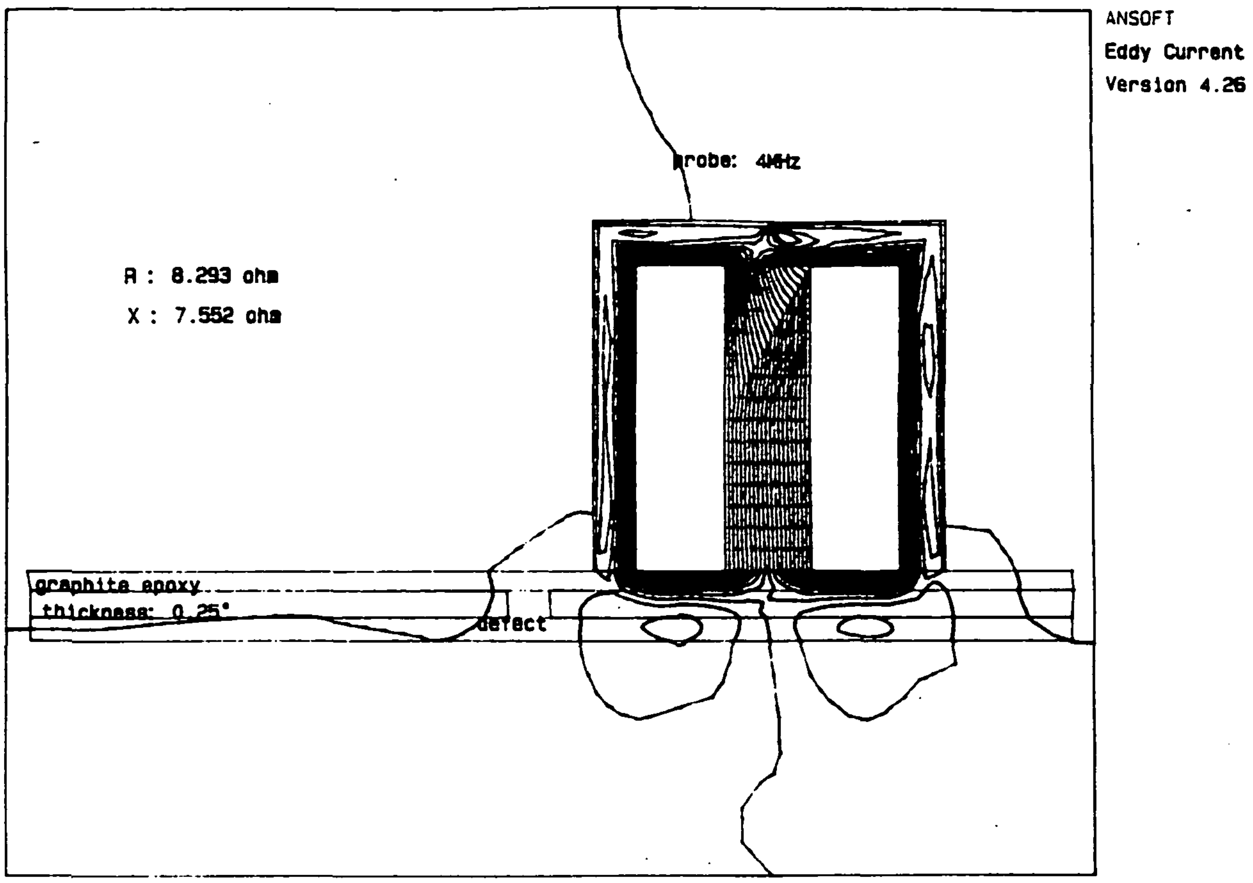

MESH MAKER
SET THE SCALE
SPECIFY THE MATERIAL AND GEOMETRIC PATTERN
GENERATE THE MESH
SKIN DEPTH > 1/2(MESH TRIANGLES)
NO
YES
REFINE THE MESH
SAVE THE MESH
MAXWELL SOLVER
READ THE MESH
SPECIFY THE MATERIAL PROPERTY (CONDUCTIVITY, PERMEABILITY, PERMITTIVITY)
SET THE FREQUENCY AND BOUNDARY CONDUCTION
SOLVE THE PROBLEM
POST THE FIELD OR CURRENT LINES

FIGURE 13. FINITE ELEMENT MODEL OF GRAPHITE FIBER SCAN OVER INTERNAL DEFECT



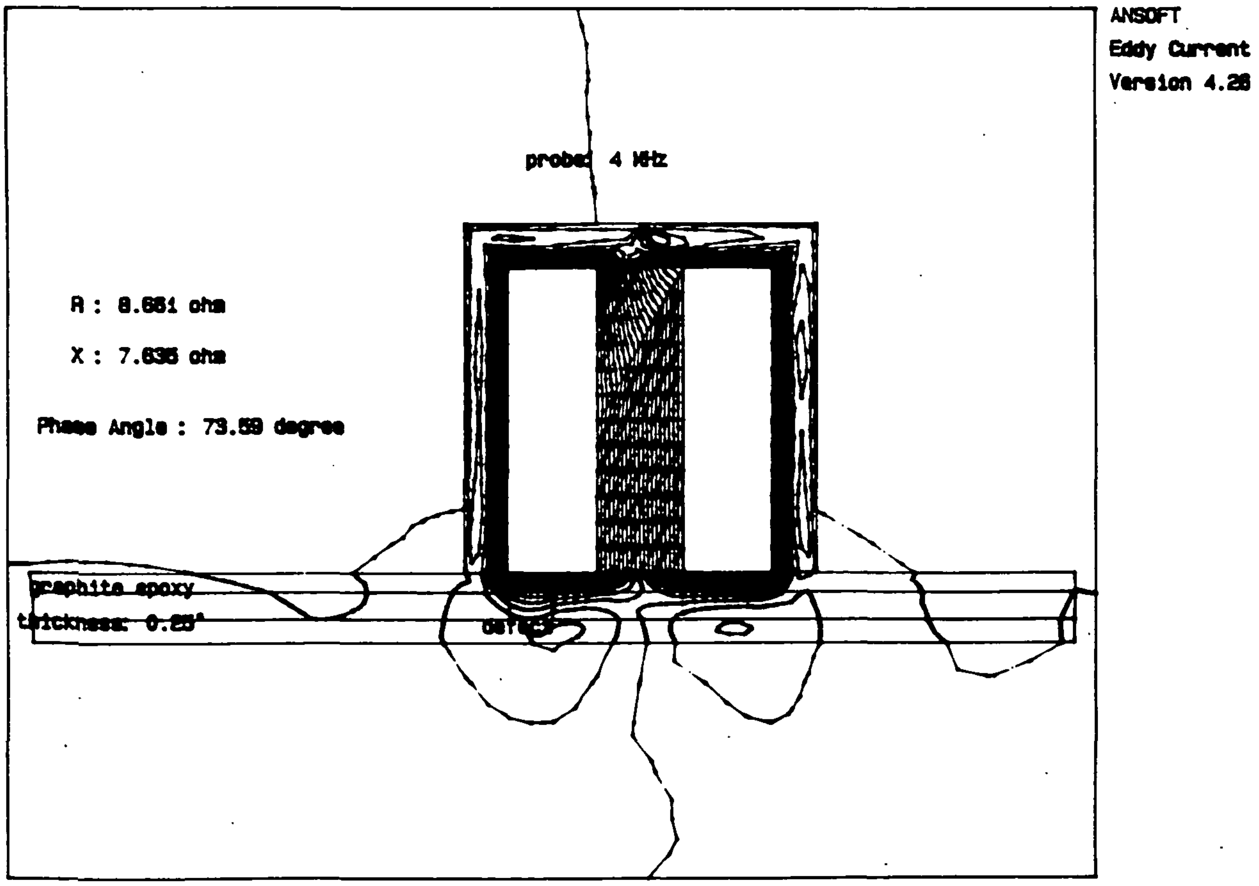
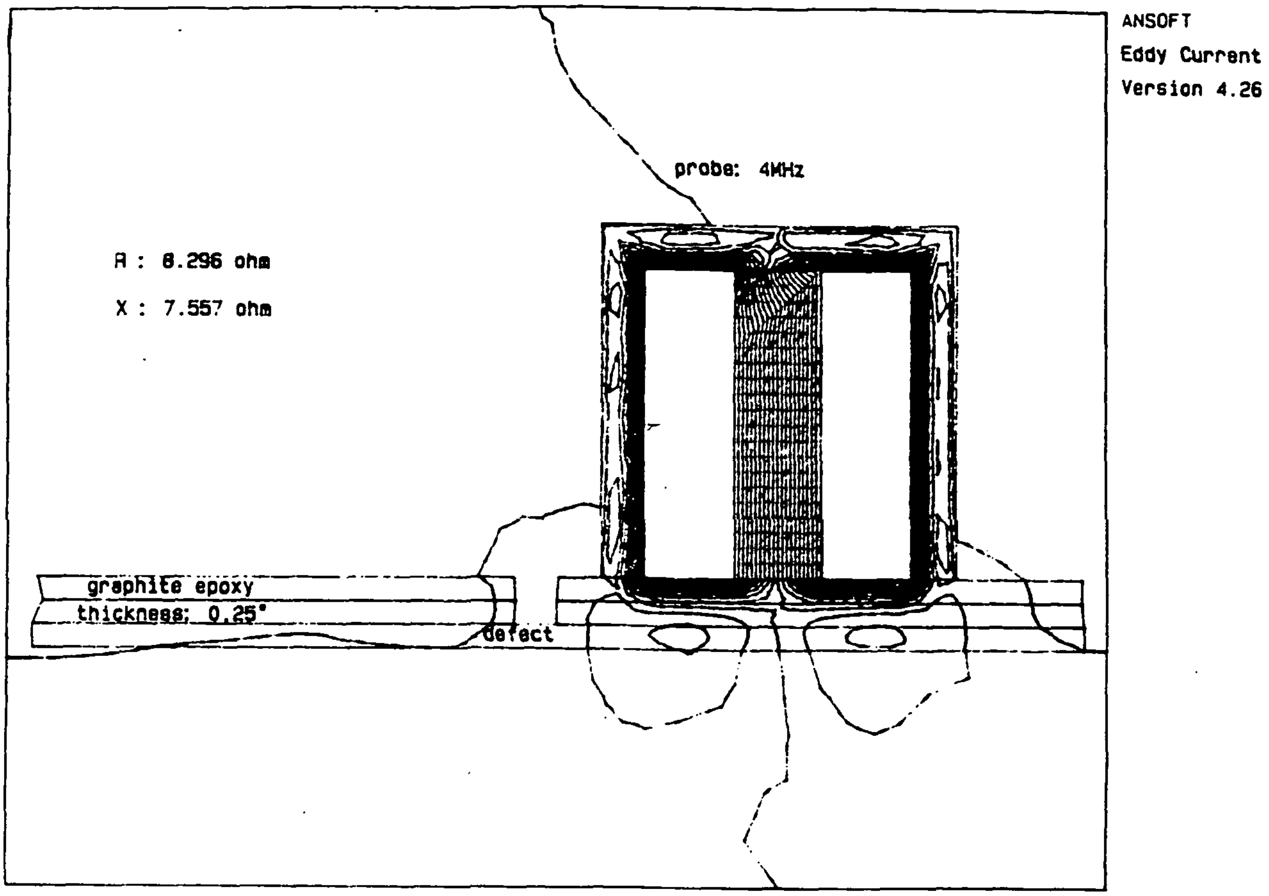


FIGURE 14. FINITE ELEMENT MODEL OF GRAPHITE FIBER SCAN OVER SURFACE DEFECT



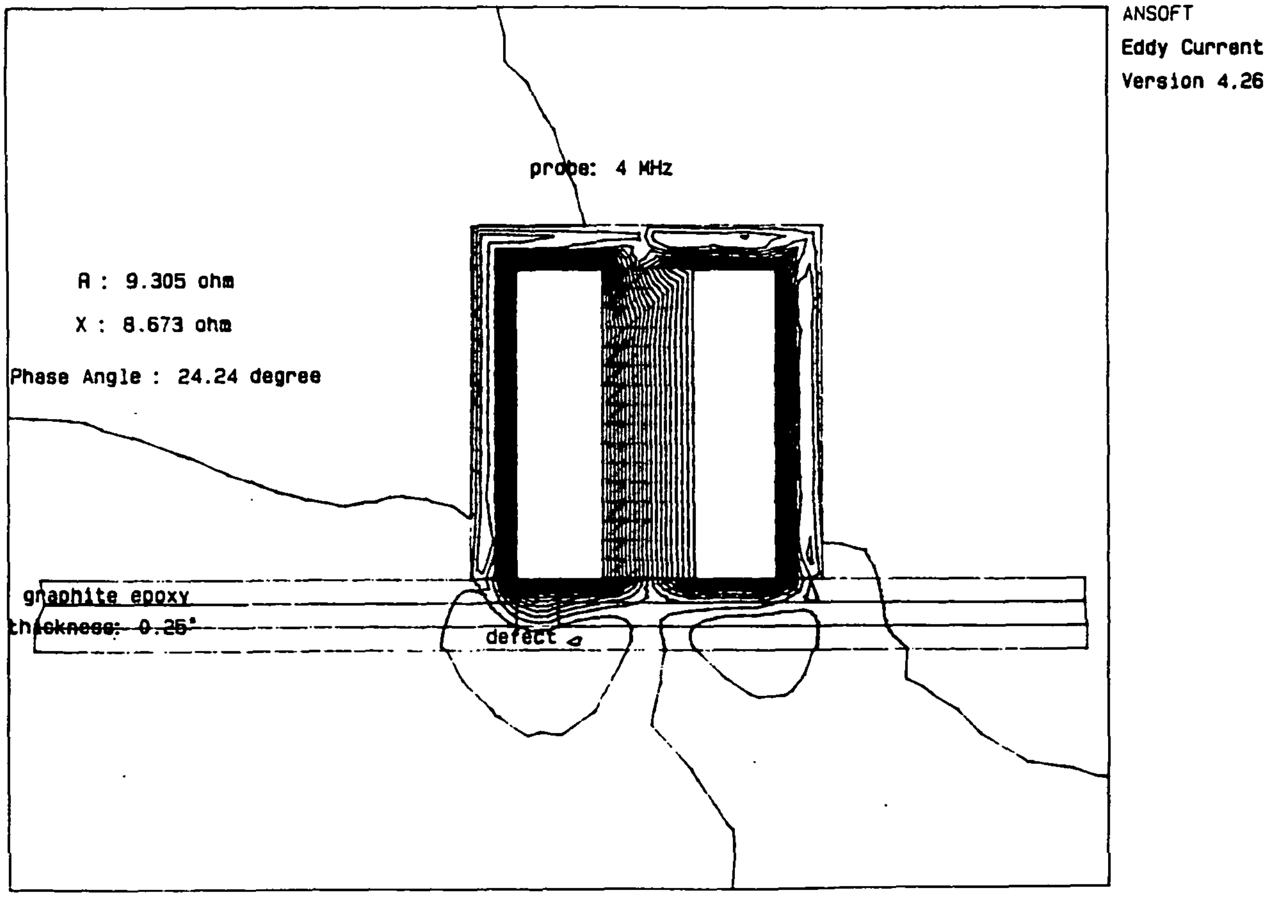
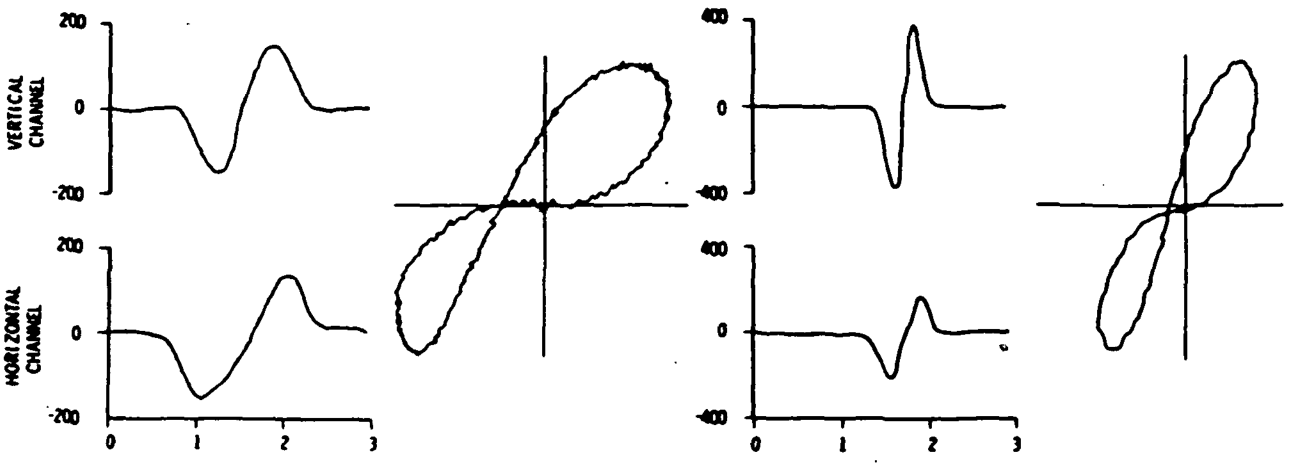


FIGURE 15. EXAMPLE O: ATISTICAL PATTERN RECOGNITION TECHNIQUE

EDDY CURRENT SIGNALS FROM DIFFERENT TYPES OF FLAWS IN AUSTENITIC STEEL



SUB-SURFACE ELLIPTICAL FLAW

UNIFORM THINNING FLAW

ref. Doctor, et. al.

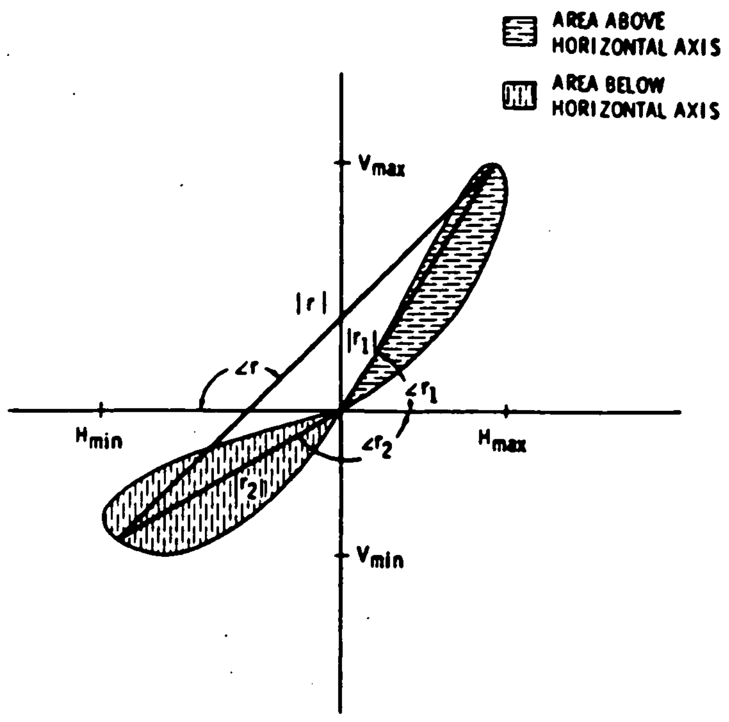
FEATURES USED IN PATTERN RECOGNITION STUDY

Feature	Definitions	Description
1	$C_{HH} = 1/N \Sigma h_i^2$	Power in horizontal channel
2	$C_{VV} = 1/N \Sigma v_i^2$	Power in vertical channel
3	C_{VV}/C_{HH}	Ratio of power
4	$\sqrt{C_{VV}C_{HH}}$	Geometric mean of power
5	$C_{HV}/\sqrt{C_{HH}C_{VV}}$	Correlation
6	λ_1	Maximum eigenvalue of the power matrix
7	λ_2	Minimum eigenvalue of the power matrix
8	$\lambda_1 \lambda_2$	Product of eigenvalues
9	$\angle \lambda_1$	Angle of eigenvector corresponding to the maximum eigenvalue
10	$(H_{max} - H_{min})/\sqrt{C_{HH}}$	Horizontal voltage (peak-to-peak)
11	$(V_{max} - V_{min})/\sqrt{C_{VV}}$	Vertical voltage (peak-to-peak)
12	$\lvert r \rvert$	Length of the radial vector
13	$\angle r$	Angle of the radial vector
14	...	Area of Lissajous pattern above the horizontal axis
15	...	Area of lower lobe of Lissajous pattern below the horizontal axis
16	$\lvert r_1 \rvert$	Length of upper lobe
17	$\angle r_1$	Angle of upper lobe
18	$\lvert r_2 \rvert$	Length of lower lobe
19	$\angle r_2$	Angle of lower lobe
20	...	Vertical-channel autocorrelation at Lag 40
21	...	Vertical-channel autocorrelation at Lag 60
22	...	Vertical-channel autocorrelation at Lag 87
23	...	Vertical-channel maximum frequency response
24	...	Vertical-channel frequency of maximum response
25	...	Vertical-channel total power
26	...	Vertical-channel first moment
27	...	Vertical-channel second moment

ref. P. G. Doctor, et al

FIGURE 16. CONTINUED EXAMPLE OF STATISTICAL PATTERN RECOGNITION TECHNIQUE

DEFINITIONS OF SELECTED SHAPE PARAMETERS



ref. P. G. Doctor, et al.

DEFINITIONS OF USEFUL PARAMETERS FOR FEATURE ANALYSIS

AUTOCORRELATION FUNCTION REPRESENTATION

$$C_k = \frac{\Sigma (v_{k+i} - \bar{v})(v_i - \bar{v})}{\Sigma (v_i - \bar{v})^2}$$

k = 0,1, etc. ≡ separation between two points of the digitized waveform

$C_0 = 1$; $-1 \le C_k \le 1$

MOMENTS IN THE FREQUENCY DOMAIN

$M_0 = \Pi\, p(w)\, dw$ p(w) = power spectral density

$M_1 = \Pi\, wp(w)\, dw$

$M_2 = \Pi\, w^2p(w)\, dw$

ref. Doctor, etc.

FIGURE 17. MODEL OF EXPERT SYSTEM FOR AUTOMATED EDDY CURRENT ANALYSIS

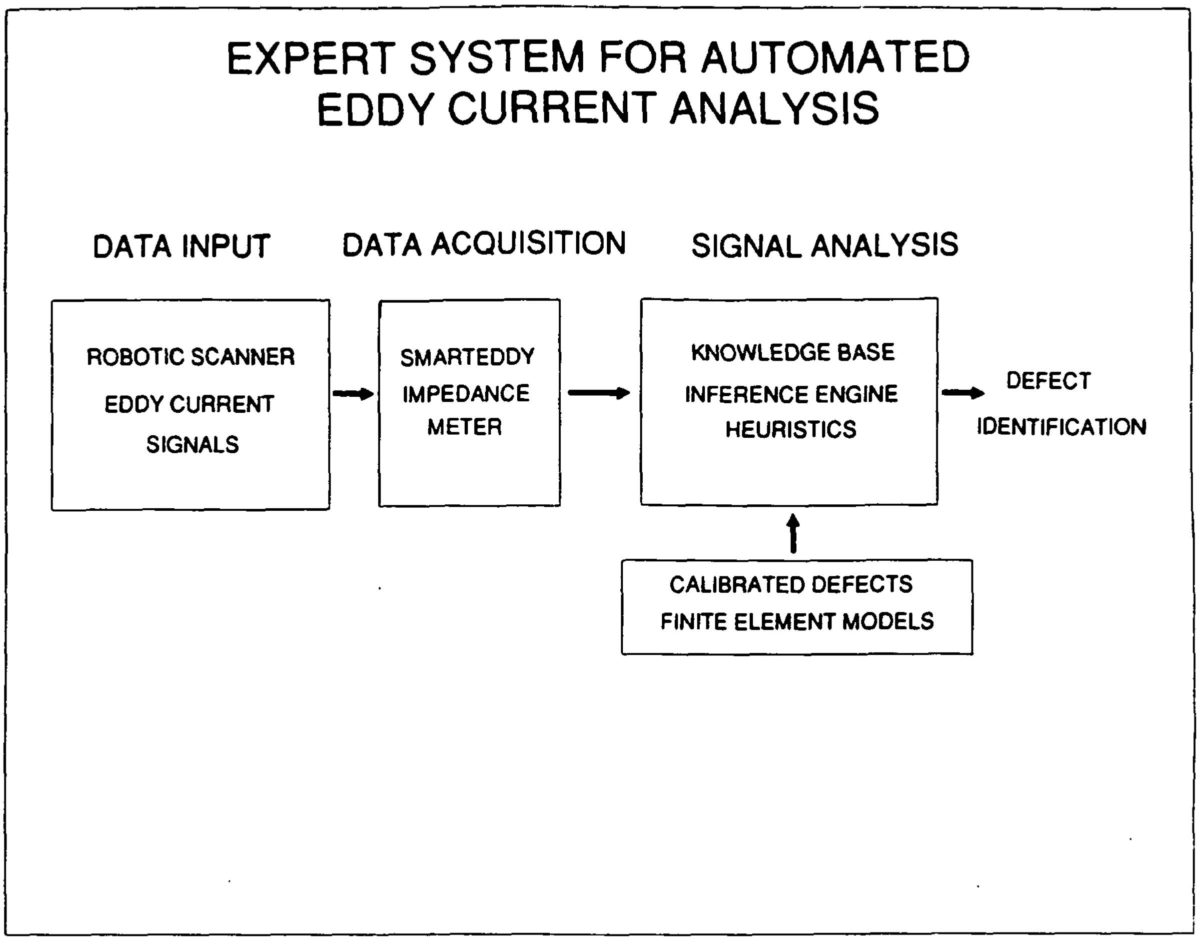

EXPERT SYSTEM FOR AUTOMATED EDDY CURRENT ANALYSIS
DATA INPUT
DATA ACQUISITION
SIGNAL ANALYSIS
ROBOTIC SCANNER EDDY CURRENT SIGNALS
SMARTEDDY IMPEDANCE METER
KNOWLEDGE BASE INFERENCE ENGINE HEURISTICS
DEFECT IDENTIFICATION
CALIBRATED DEFECTS FINITE ELEMENT MODELS

FIGURE 18. EXPERT SYSTEM ARCHITECTURE FOR EDDY CURRENT ANALYSIS.

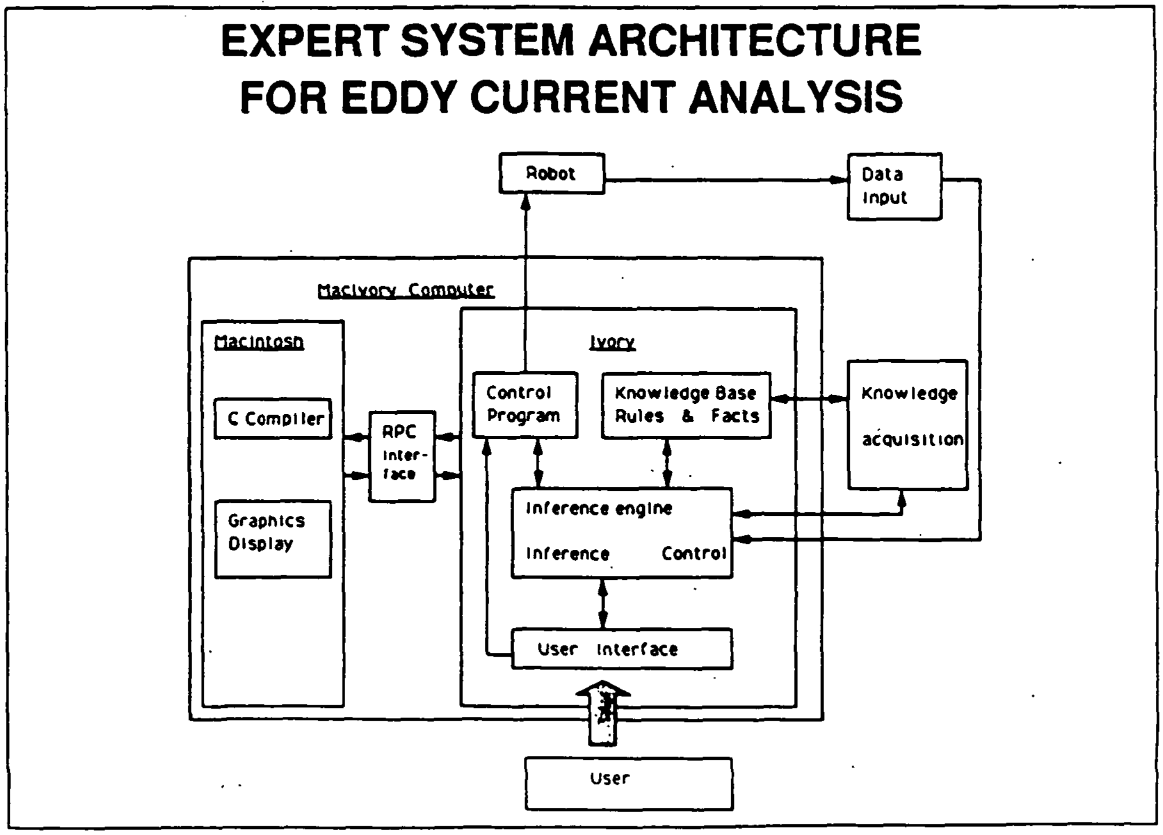
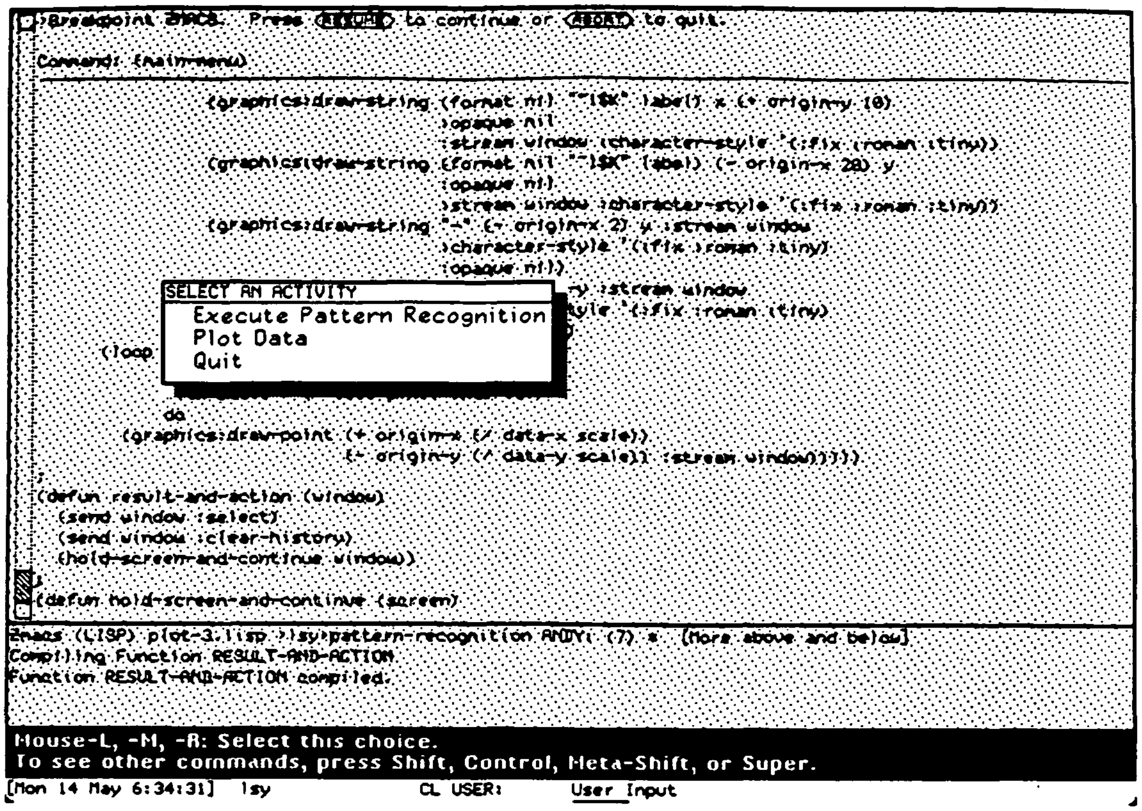


FIGURE 19. SCREENS FOR USER SELECTION OF OPTIONS ON MACIVORY SYSTEM.

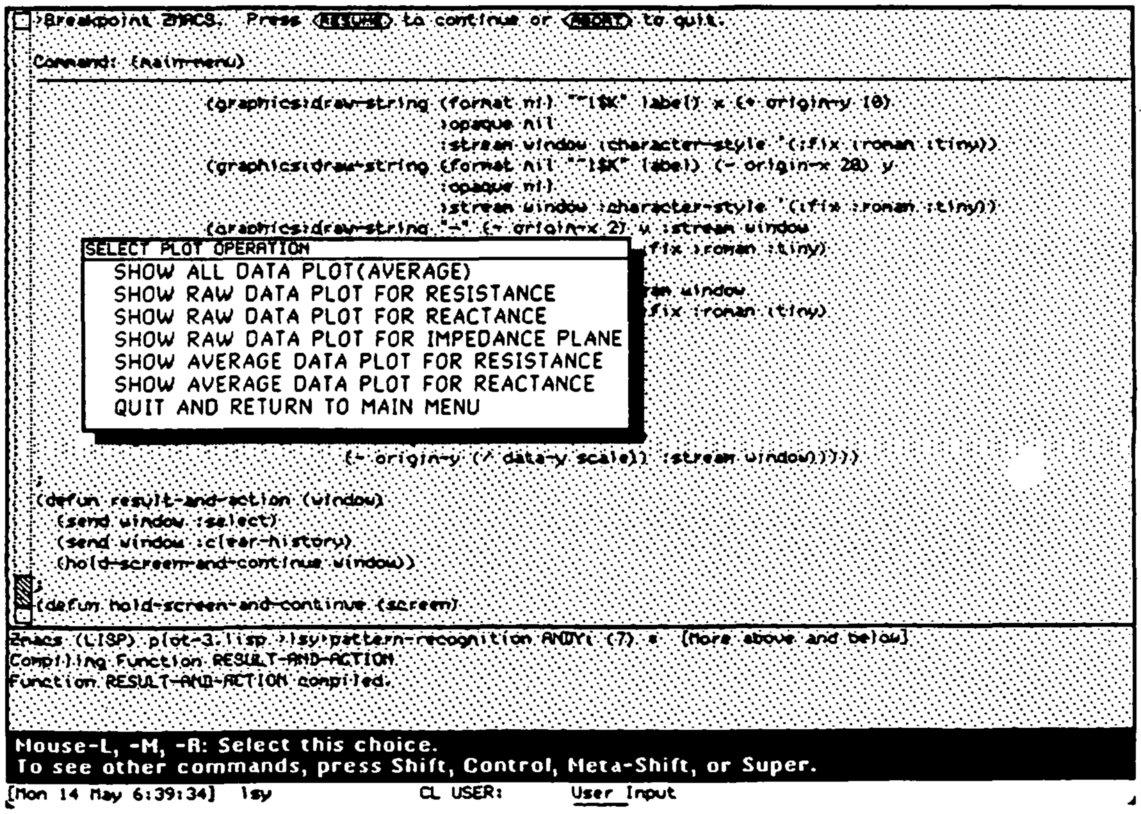


```
Breakpoint ZMACS. Press RESUME to continue or ABORT to quit.

Command: (main-menu)
                (graphics:draw-string (format nil "~1$X" label) x (+ origin-y 10)
                                      :opaque nil
                                      :stream window :character-style '(:fix :roman :tiny))
                (graphics:draw-string (format nil "~1$X" label) (- origin-x 20) y
                                      :opaque nil
                                      :stream window :character-style '(:fix :roman :tiny))
                (graphics:draw-string "-" (- origin-x 2) y :stream window
                                      :character-style '(:fix :roman :tiny)
                                      :opaque nil))
       SELECT AN ACTIVITY                    -y :stream window
         Execute Pattern Recognition        tyle '(:fix :roman :tiny)
         Plot Data
   (loop Quit

        do
      (graphics:draw-point (+ origin-x (/ data-x scale))
                           (- origin-y (/ data-y scale)) :stream window))))
;
(defun result-and-action (window)
  (send window :select)
  (send window :clear-history)
  (hold-screen-and-continue window))
;
(defun hold-screen-and-continue (screen)
Zmacs (LISP) plot-3.lisp >lsy>pattern-recognition ANDY: (7) *  [More above and below]
Compiling Function RESULT-AND-ACTION
Function RESULT-AND-ACTION compiled.

Mouse-L, -M, -R: Select this choice.
To see other commands, press Shift, Control, Meta-Shift, or Super.
[Mon 14 May 6:34:31]  lsy            CL USER:      User Input
```



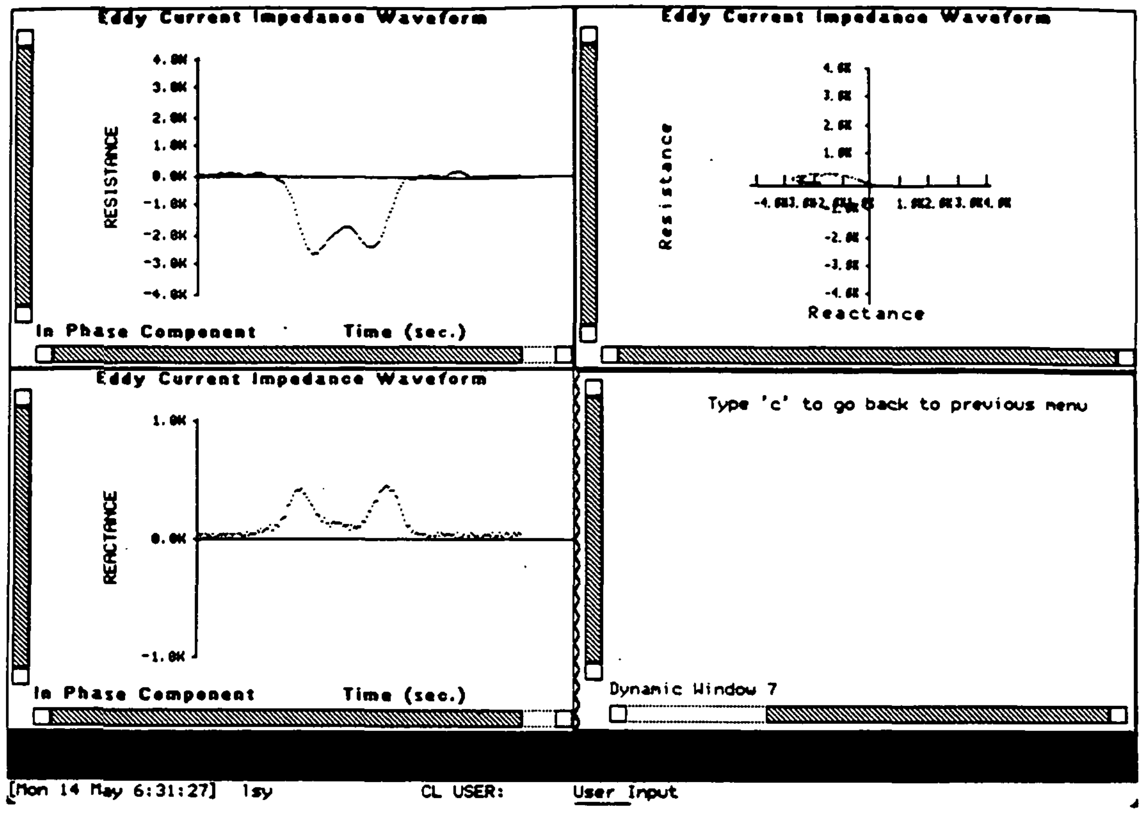
```
Breakpoint ZMACS. Press RESUME to continue or ABORT to quit.

Command: (main-menu)
                (graphics:draw-string (format nil "~1$X" label) x (+ origin-y 10)
                                      :opaque nil
                                      :stream window :character-style '(:fix :roman :tiny))
                (graphics:draw-string (format nil "~1$X" label) (- origin-x 20) y
                                      :opaque nil
                                      :stream window :character-style '(:fix :roman :tiny))
                (graphics:draw-string "-" (- origin-x 2) y :stream window
  SELECT PLOT OPERATION                                 fix :roman :tiny)
    SHOW ALL DATA PLOT(AVERAGE)
    SHOW RAW DATA PLOT FOR RESISTANCE                 am window
    SHOW RAW DATA PLOT FOR REACTANCE                  fix :roman :tiny)
    SHOW RAW DATA PLOT FOR IMPEDANCE PLANE
    SHOW AVERAGE DATA PLOT FOR RESISTANCE
    SHOW AVERAGE DATA PLOT FOR REACTANCE
    QUIT AND RETURN TO MAIN MENU

                           (- origin-y (/ data-y scale)) :stream window))))
;
(defun result-and-action (window)
  (send window :select)
  (send window :clear-history)
  (hold-screen-and-continue window))
;
(defun hold-screen-and-continue (screen)
Zmacs (LISP) plot-3.lisp >lsy>pattern-recognition ANDY: (7) *  [More above and below]
Compiling Function RESULT-AND-ACTION
Function RESULT-AND-ACTION compiled.

Mouse-L, -M, -R: Select this choice.
To see other commands, press Shift, Control, Meta-Shift, or Super.
[Mon 14 May 6:39:34]  lsy            CL USER:      User Input
```

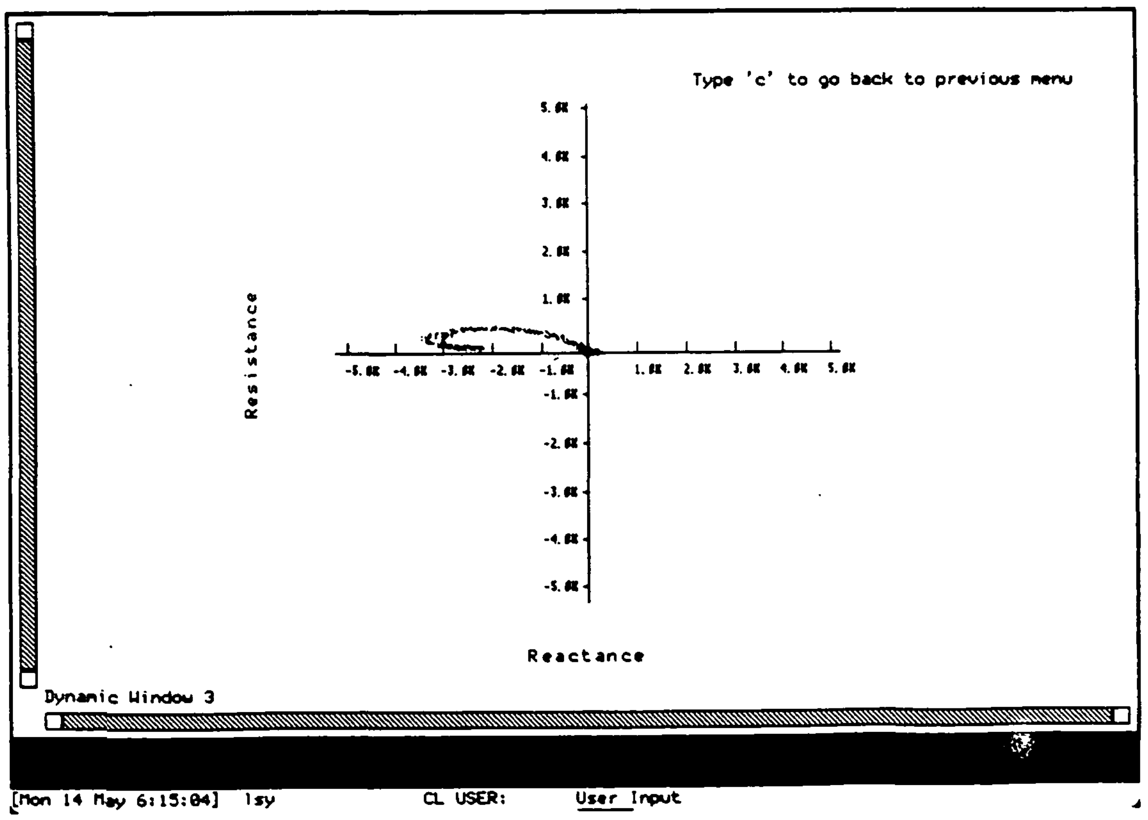
FIGURE 20. DISPLAYS OF EDDY CURRENT DATA USING MACIVORY SOFTWARE.



Type 'c' to go back to previous menu

Dynamic Window 7

[Mon 14 May 6:31:27] lsy CL USER: User Input

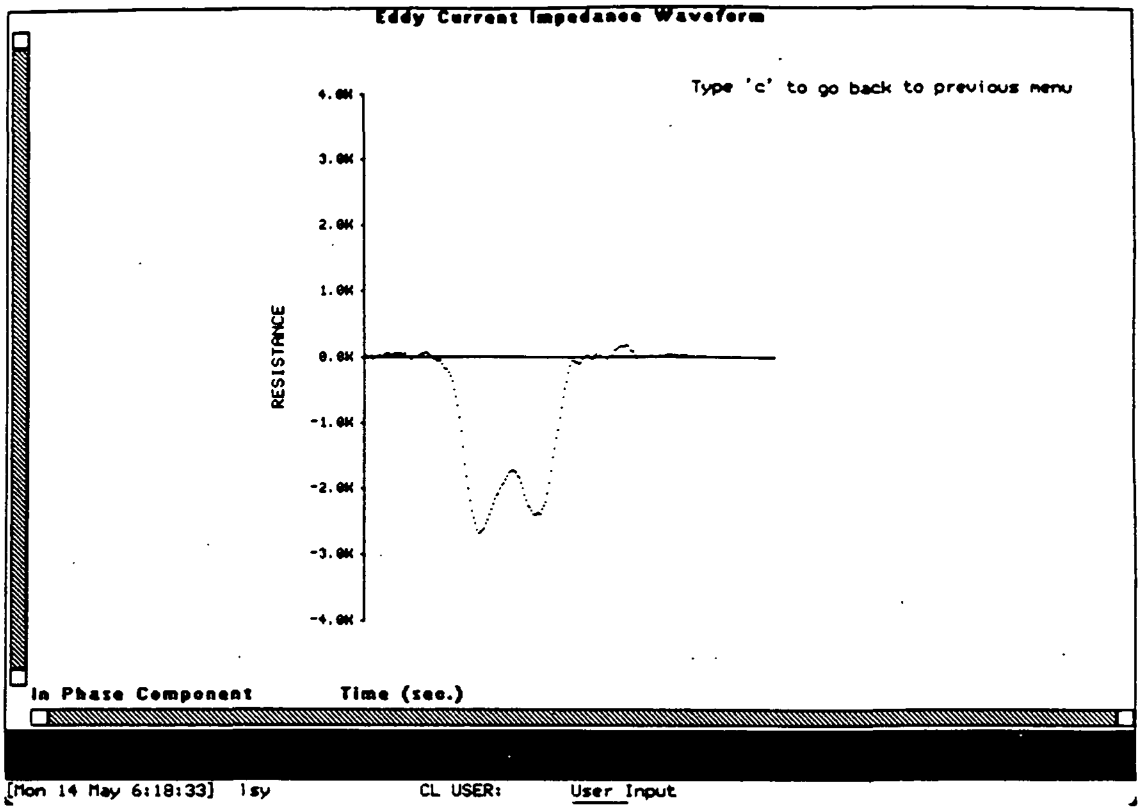


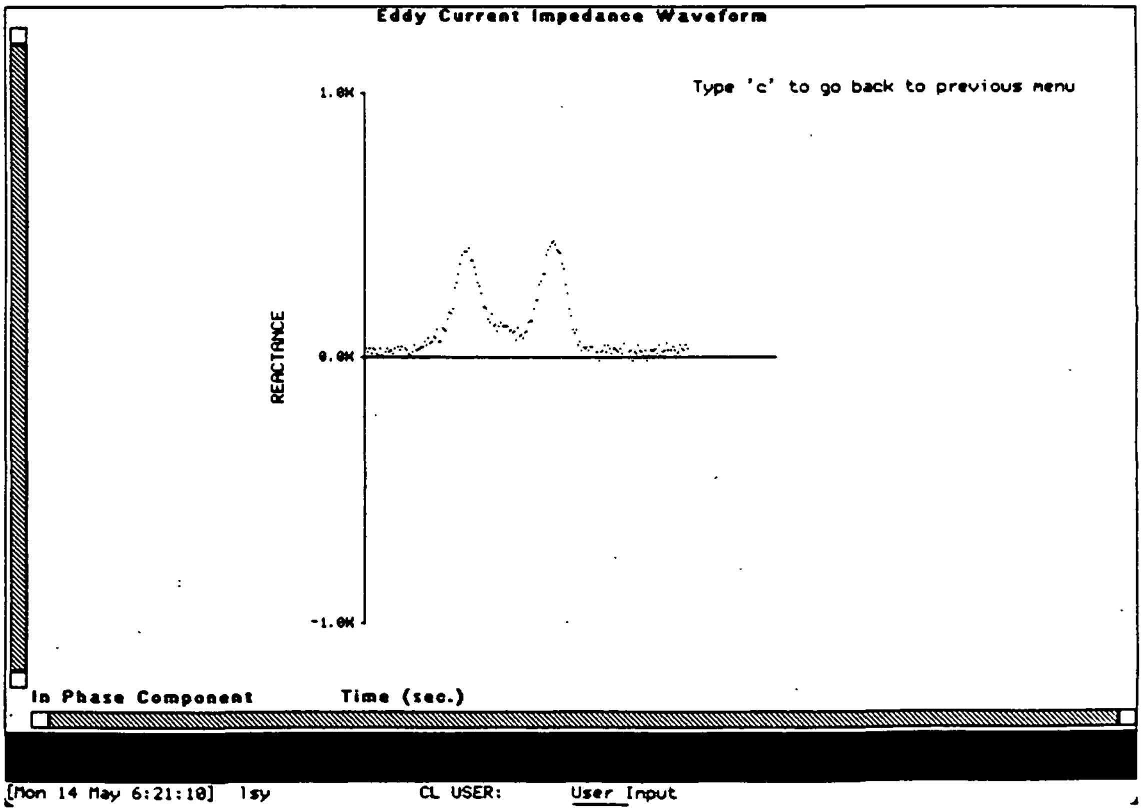
Type 'c' to go back to previous menu

Dynamic Window 3

[Mon 14 May 6:15:04] lsy CL USER: User Input

FIGURE 21. DISPLAYS OF EDDY CURRENT DATA USING MACIVORY SOFTWARE (CONTINUED).





APPENDICIES

```
 ;;; ;;; -*- Syntax: Common-Lisp; Package: COMMON-LISP-USER; Base: 10;
Mode: LISP -*-
;;;
;;;-Global Variables-
(defvar  *window-size*)
(defvar  *resistance*  nil)
(defvar  *reactance*  nil)
(defvar  *resistance-average*  nil)
(defvar  *reactance-average*  nil)
(defvar  *phase-angle*  nil)
(defvar  *pathname*)
(defvar  *menu-window*  (tv:make-window  'dw:dynamic-window
                  :blinker-p nil
                  :expose-p nil
                  ; :default-character-style '(:eurex :italic :large)
                  :more-p nil
                  :save-bits t))
;
(defvar  *plot-detail-window*  (tv:make-window  'dw:dynamic-window
                  :blinker-p nil
                  :expose-p nil
                  :more-p nil
                  :save-bits t
                   :margin-components
                   '((dw:margin-borders :thickness 1)
                    (dw:margin-label :margin :top
                                :style (:swiss :bold :small)
                                :string "Eddy Current Impedance
                                   Waveform"
                                :centered-p t)
                     (dw:margin-scroll-bar  :margin  :bottom)
                     (dw:margin-scroll-bar  :margin  :left)
                     (dw:margin-label  :margin  :bottom
                                :style (:swiss :bold :small)
                                :string "In Phase Component        Time
                                   (sec.)"))))
;
(defvar  *plot-detail-window-1*  (tv:make-window  'dw:dynamic-window
                  :blinker-p nil
                  :expose-p nil
                  :more-p nil
                  :save-bits t))
```

```
;
(defvar  *sample-window-1*  (tv:make-window  'dw:dynamic-window
               :blinker-p nil
               :expose-p nil
               :more-p nil
               :save-bits t
                :margin-components
               '((dw:margin-borders  :thickness  1)
                  (dw:margin-label :margin :top
                              :style (:swiss :bold :small)
                              :string "Eddy Current Impedance
                                 Waveform"
                              :centered-p  t)
                  (dw:margin-scroll-bar  :margin  :bottom)
                  (dw:margin-scroll-bar  :margin  :left)
                  (dw:margin-label :margin  :bottom
                              :style (:swiss :bold :small)
                              :string "In Phase Component        Time
                                 (sec.)"))))
;
(defvar  *sample-window-2*  (tv:make-window  'dw:dynamic-window
               :blinker-p nil
               :expose-p nil
               :more-p nil
               :save-bits t
                :margin-components
               '((dw:margin-borders  :thickness  1)
                  (dw:margin-label :margin :top
                              :style (:swiss :bold :small)
                              :string "Eddy Current Impedance
                                 Waveform"
                              :centered-p  t)
                  (dw:margin-scroll-bar  :margin  :bottom)
                  (dw:margin-scroll-bar  :margin  :left)
                  (dw:margin-label :margin  :bottom
                              :style (:swiss :bold :small)
                              :string "In Phase Component        Time
                                 (sec.)"))))
```

```
;
(defvar *sample-window-3* (tv:make-window 'dw:dynamic-window
                :blinker-p nil
                :expose-p nil
                :more-p nil
                :save-bits t
                 :margin-components
                '((dw:margin-borders :thickness 1)
                  (dw:margin-label :margin :top
                            :style (:swiss :bold :small)
                            :string "Eddy Current Impedance
                                   Waveform"
                            :centered-p t)
                  (dw:margin-scroll-bar :margin :bottom)
                  (dw:margin-scroll-bar :margin :left))))
;
(defvar *sample-window-4* (tv:make-window 'dw:dynamic-window
                :blinker-p nil
                :expose-p nil
                :more-p nil
                :save-bits t))
;
(defun configure-windows ()
   (multiple-value-bind (screen-left screen-top screen-right screen-bottom)
   (send tv:main-screen :inside-edges)
   (let ((width (truncate (/ (- screen-right screen-left) 2)))
       (height (truncate (/ (- screen-bottom screen-top) 2))))
       (send *sample-window-1* :set-edges screen-left screen-top
                                width height)
       (send *sample-window-2* :set-edges screen-left height
                                width screen-bottom)
       (send *sample-window-3* :set-edges width screen-top
                                screen-right height)
       (send *sample-window-4* :set-edges width height
                                screen-right screen-bottom))))
```

```
;;
;;-MAIN PROGRAM-
;
(defun eddy-current ()
   (send *menu-window* :select)
   (send *menu-window* :clear-history)
   (general-information)
   (configure-windows)
   (input-data-file)
  (data)
   (main-menu)
   (send *terminal-io* :select))


;
(defun general-information ()
  (format *menu-window* "~2%~10TPATTERN RECOGNITION FOR EDDY
                                        CURRENT")
  (format *menu-window* "~20%~10TPRESS 'C' TO CONTINUE")
   (loop as char = (send *menu-window* :any-tyi)
        until (member char '(#\c #\C)))
   (send *menu-window* :clear-history))
;
(defun input-data-file ()
  (format *menu-window* "~%please type data file name,")
  (format *menu-window* "~%~%example data file: test.dat, Press Control
                                        Abort to exit program.>>")
  (let ((file (zl:readline *menu-window*)))
       (setq *pathname* (string-append "andy:>lsy>pattern-recognition>")
                    (string file)))))
;
(defun main-menu ()
  (loop
      as selection = (dw:menu-choose
                     '(("Execute Pattern Recognition" pattern-recognition)
                      ("Plot Data" plot-data)
                     ("Quit" quit))
                   :prompt "SELECT AN ACTIVITY"
                     :momentary-p nil)
     until (equal 'quit selection)
      do
     (execute-command selection)
     (send *terminal-io* :select)))
;
```

```
(defun  execute-command  (command)
    (cond  ((equal  command  'plot-data)  (plot-data-menu))
           ((equal  command  'pattern-recognition)  (pattern-recognition))))
;
(defun  plot-data-menu  ()
    (loop  as  selection  =  (dw:menu-choose
                      '(("SHOW ALL DATA PLOT(AVERAGE)" show-all)
                       ("SHOW RAW DATA PLOT FOR RESISTANCE" raw-
                            resistance)
                       ("SHOW RAW DATA PLOT FOR REACTANCE" raw-
                            reactance)
                       ("SHOW RAW DATA PLOT FOR IMPEDANCE PLANE"
                            impedance)
                      ("SHOW AVERAGE DATA PLOT FOR RESISTANCE"
                            average-resistance)
                       ("SHOW AVERAGE DATA PLOT FOR REACTANCE" average-
                            reactance)
                       ("QUIT AND RETURN TO MAIN MENU" quit))
                      :prompt "SELECT PLOT OPERATION"
                         :momentary-p nil)
        until  (equal  'quit  selection)
         do
        (cond  ((equal  selection  'show-all)  (show-all))
              ((equal  selection  'raw-reactance)  (plot-full-reac  *plot-detail-
                                                                window*))
              ((equal  selection  'raw-resistance)  (plot-full-resi  *plot-detail-
                                                                window*))
           ((equal  selection  'impedance)  (plot-full-impedance  *plot-detail-
                                                                window-1*))
              ((equal  selection  'average-resistance)  (plot-full-resi-avg  *plot-
                                                                detail-window*))
              ((equal  selection  'average-reactance)  (plot-full-reac-avg  *plot-
                                                         detail-window*)))))
;
(defun  plot-full-reac  (window)
  (plot-wave-form  window  *reactance*  "REACTANCE")
   (hold-screen-and-continue  window))
;
(defun  plot-full-resi  (window)
  (plot-wave-form  window  *resistance*  "RESISTANCE")
   (hold-screen-and-continue  window))
;
```

```
(defun plot-full-impedance (window)
  (plot-impedance-plane window *resistance* *reactance*)
   (hold-screen-and-continue window))
;
(defun plot-full-resi-avg (window)
  (plot-wave-form window *resistance-average* "RESISTANCE")
   (hold-screen-and-continue window))
;
(defun plot-full-reac-avg (window)
  (plot-wave-form window *reactance-average* "REACTANCE")
   (hold-screen-and-continue window))
;
(defun show-all ()
    (plot-wave-form *sample-window-1* *resistance-average*
                                      "RESISTANCE")
   (plot-wave-form *sample-window-2* *reactance-average* "REACTANCE")
    (plot-impedance-plane *sample-window-3* *resistance-average*
                                      *reactance-average*)
    (result-and-action *sample-window-4*))
;
(defun plot-wave-form (window data string-name)
  (send window :select)
  (send window :clear-history)
  (let ((origin-x (* 3/10 (send window :inside-width)))
      (origin-y (* 1/2 (send window :inside-height)))
      (y-axis-length (- (* 9/10 (send window :inside-height))
                        (* 1/10 (send window :inside-height))))
      (x-axis-length (+ 50 (length data)))
      (max (apply #'max data))
      (min (apply #'min data))
          (label-num) (y-interval-pixel) (y-axis-bottom) (y-axis-begin)
      (y-axis-end))
     (setq y-axis-begin (- origin-y (* 1/2 y-axis-length))
          y-axis-end (+ origin-y (* 1/2 y-axis-length)))
     (graphics:draw-line origin-x y-axis-begin origin-x y-axis-end
               :stream window)
     (graphics:draw-line origin-x origin-y (+ origin-x x-axis-length) origin-y
               :stream window)
     (graphics:with-room-for-graphics (window origin-y)
       (graphics:draw-string-image string-name 0 0
                          :stream window
                          :translation (list (- origin-x 45) 0)
                          :attachment-x :center
```

```
                    :rotation (/ pi 2)))
   (cond ((> (abs max) (abs min))
                      (setq label-num (ceiling (abs max) 1000)))
        (t             (setq label-num (+ 1 (ceiling (abs min) 1000)))))
    (setq y-interval-pixel (floor y-axis-length (* 2 label-num)))
    (setq y-axis-bottom (+ origin-y (* y-interval-pixel label-num)))
   (loop for label from (- label-num) to  label-num
      for y       from y-axis-bottom by (- y-interval-pixel)
      do
     (graphics:draw-string (format nil "~1$K" label) (- origin-x 5) y
                         :stream window :opaque nil :attachment-y :center
                  :character-style '(:fix :roman :small)
                  :attachment-x  :right)
     (graphics:draw-line (- origin-x 2) y origin-x y :stream window))
   (loop for data-pt in data
      for x from (+ origin-x 1) by 1
       with scale = (/ 1000 y-interval-pixel)
      do
     (graphics:draw-circle x (- origin-y (/ data-pt scale)) 0.5
                         :stream window))))
;
(defun plot-impedance-plane (window resi-data reac-data)
  (send window :select)
  (send window :clear-history)
  (graphics:with-graphics-scale (window 1.25)
   (let ((origin-x (/ (* 1/2 (send window :inside-width)) 1.25))
       (origin-y (/ (* 1/2 (send window :inside-height)) 1.25))
       (x-axis-length (send window :inside-width))
       (y-axis-length (send window :inside-height))
       (max-resi (apply #'max resi-data))
       (min-resi (apply #'min resi-data))
       (max-reac (apply #'max reac-data))
       (min-reac (apply #'min reac-data))
       (x-axis-begin) (x-axis-end)(y-axis-begin) (y-axis-end)
       (label-num) (x-axis-start) (y-axis-start) (pixel-interval)
       (axis-length))
    (cond ((> y-axis-length x-axis-length)
         (setq axis-length (- (* 8/10 (send window :inside-width))
                              (* 2/10 (send window :inside-width)))))
         (t  (setq axis-length (- (* 8/10 (send window :inside-height))
                             (* 2/10 (send window :inside-height))))))
    (setq x-axis-begin (- origin-x (* 1/2 axis-length))
       x-axis-end    (+ origin-x (* 1/2 axis-length))
      y-axis-begin (- origin-y (* 1/2 axis-length))
      y-axis-end   (+ origin-y (* 1/2 axis-length)))
   (graphics:draw-line x-axis-begin origin-y x-axis-end origin-y :stream
      window)
   (graphics:draw-line origin-x y-axis-begin origin-x y-axis-end :stream
      window)
   (graphics:with-room-for-graphics (window origin-y)
 (graphics:draw-string-image "Resistance" 0 0
                        :stream window
                        :translation (list (- x-axis-begin 35) 0)
                        :attachment-x :center
                        :rotation (/ pi 2))
 (graphics:draw-string-image  "Reactance" 0 0
                        :stream window
                        :translation (list origin-x (+ (- origin-y) 0))
                        :attachment-x :center
                        :attachment-y :center))
  (cond ((> (abs max-resi) (max (abs max-reac) (abs min-resi) (abs min-
      reac)))
      (setq label-num (ceiling (abs max-resi) 1000)))
     ((> (abs max-reac) (max (abs max-resi) (abs min-resi) (abs min-
      reac)))
      (setq label-num (ceiling (abs max-reac) 1000)))
     ((> (abs min-resi) (max (abs max-reac) (abs max-resi) (abs min-
      reac)))
      (setq label-num (+ 1 (ceiling (abs min-resi) 1000))))
     ((> (abs min-reac) (max (abs min-resi) (abs max-reac) (abs max-
      resi)))
      (setq label-num (+ 1 (ceiling (abs min-reac) 1000)))))
  (setq pixel-interval (floor axis-length (* 2 label-num)))
  (setq x-axis-start (- origin-x (* pixel-interval label-num))
        y-axis-start (+ origin-y (* pixel-interval label-num)))
  (loop for label from (zl:minus label-num) to label-num
      for x from x-axis-start by pixel-interval
      for y from y-axis-start by (zl:minus pixel-interval)
      when (or (not (zerop label)) (not (zerop label)))
     do
      (graphics:draw-string (format nil "~1$K" label) x (+ origin-y 10)
                        :opaque nil
                          :stream window :character-style '(:fix :roman
                        :tiny))
      (graphics:draw-string (format nil "~1$K" label) (- origin-x 20) y
                        :opaque nil
```

```
                                :stream window :character-style '(:fix :roman
                               :tiny))
             (graphics:draw-string "-" (- origin-x 2) y :stream window
                                :character-style '(:fix :roman :tiny)
                               :opaque nil)
             (graphics:draw-string "|" x origin-y :stream window
                                :character-style '(:fix :roman :tiny)
                               :opaque nil))
       (loop for data-x in resi-data
           for data-y in reac-data
           with scale = (/ 1000 pixel-interval)
          do
       (graphics:draw-point (+ origin-x (/ data-x scale))
                          (- origin-y (/ data-y scale)) :stream window)))))
;
(defun result-and-action (window)
  (send window :select)
  (send window :clear-history)
   (hold-screen-and-continue window))
;
(defun hold-screen-and-continue (screen)
   (graphics:draw-string "Type 'c' to go back to previous menu"
                   (* 6/10 (send screen :inside-width))
                   (* 1/10 (send screen :inside-height))
                   :stream screen)
   (loop as char = (send screen :any-tyi)
     until (member char '(#\c #\C))))
(defun data ()
  (loop with data = (get-data)
      with resistance-sum = 0
      with reactance-sum = 0
      with resistance-averages = nil
      with reactance-averages = nil
      ;with phase-angle = nil
      with num-data = (accept 'integer
                         :stream *menu-window*
                         :prompt
                         "please type the number of data for calculating
                         average")
      for resistance in data by #'cddr
      for reactance in (cdr data) by #'cddr
      for count from 1
      collect resistance into resistance-list
      collect reactance into reactance-list
      ; do
      ;(setq phase-angle (cons (- 180 (* (atan reactance resistance) (/ 180
           (float pi 1.0)))) phase-angle))
      if (zerop (mod count num-data))
        do
            (setq resistance-averages (cons (/ resistance-sum num-data)
             resistance-averages)
               reactance-averages (cons (/ reactance-sum num-data)
                  reactance-averages)
               resistance-sum 0
               reactance-sum 0)
      else
        do
           (setq resistance-sum (+ resistance-sum resistance)
               reactance-sum (+ reactance-sum reactance))
     finally  (setq *resistance* resistance-list *reactance* reactance-list
                  *resistance-average* (reverse resistance-averages)
                *reactance-average* (reverse reactance-averages))))
              ; *phase-angle* (reverse phase-angle)))
;
(defun get-data ()
    (with-open-file (data-stream *pathname*
                  :direction :input
                  :error     :reprompt)
      (loop while (listen data-stream)
         collect (read data-stream))))
```

PROGRAM RSMED.C

This program is used to perform the data analysis and plot various eddy current graphs for display purposes. Much of this program is based upon the software originally written in BASIC by Dr. Brian Lempriere and his group at Boeing Aerospace in Seattle.

```
# include <math.h>
# include <fcntl.h>
# include <stdio.h>
# include <alloc.h>
# include <graphics.h>
# include <stdlib.h>
# include <string.h>
# include <process.h>
# include "worlddr.h"
# include "segraph.h"
# include "asyncxx.h"
# include "hpplot.h"

      int err, i, n, grcolor, l;
      char xtitle[80];
      float *vi, *vq, *vph, *fdata;
      void ptime(float *vi, float *vq, float *vph, float *fdata, int l);
      void impedanc(float *vi, float *vq, int l);

main()
{
 int i=0, j=0, k, kk, jj, lth, hl;
 int lsb1, msb1, lsb2, msb2;
 float *RO, gh, hg, dd=0., ee=0.,xyd, xye, f;
 float rr, A1, B1, C1, D1, xu, yu, xerr, yerr;
 double d, e, xd, ye;
 char dext[] = ".dat", a[1];
 unsigned char *string1, string2[80] ;
 FILE *dstream, *stream, *handle;
 char fname[10], dname[10], ename[6], degree[5];
 char y[4], yy[4], *de;
 string1 = (unsigned char *)malloc(35000);
 RO = (float *)malloc(80);
 fdata = (float *)malloc(165000);
 vi = (float *)malloc(165000);
 vq = (float *)malloc(165000);
 vph = (float *)malloc(165000);
 printf("  Please input data file name (e.g. HOLE2) : ");
 gets(dname);
```

```
stpcpy(ename,dname);
strcat(dname,dext);
printf("  Please input rotation degree (e.g. 72) : ");
de = gets(degree);
rr = atof(de);
stream = fopen(dname, "r");
while(fgets(string2, 8, stream)!=NULL)
{
 RO[j] = atof(string2);
 j = j + 1;
}
A1 = RO[34];
B1 = RO[36];
C1 = RO[38];
D1 = RO[40];
printf("  %f  ,  %f  ,  %f  ,  %f\n",A1,B1,C1,D1);
rr = rr * 3.1415927 / 180.;
printf("  Do you want to save the ascii file? (y/n) ");
gets(y);
if(y[0] == 89 | y[0] == 121)
{
 dstream = fopen("eddy.out", "w");
}
printf("  Do you want to view the signal graphics? (y/n) ");
gets(yy);
for (k = 1; k < 5; k++)
{
 char cext[5] = ".00";
 kk = k - 1;
 itoa(kk, a, 10);
 strcat(cext, a);
 gh = 0.;
 hg = 0.;
 xerr = 0.;
 yerr = 0.;
 stpcpy(fname, ename);
 strcat(fname, cext);
 puts(fname);
 handle = fopen(fname, "rb");
 if(handle == NULL)
 exit(0);
 hl = fileno(handle);
 lth = abs(filelength(hl));
 l = lth / 8;
```

```
fread(string1, 1, lth, handle);
for(j = 0; j < l; j++)
{
   vi[j] = 0.;
   vq[j] = 0.;
   vph[j] = 0.;
}
for(j = 0; j < l; j++)
{
   jj = j * 8;
   msb1 = string1[jj + 7];
   lsb1 = string1[jj + 8];
   vi[j] = 5. * ((256. * msb1) + lsb1 - 32767.) / 32767.;
   msb2 = string1[jj + 9];
   lsb2 = string1[jj + 10];
   vq[j] = 5. * ((256. * msb2) + lsb2 - 32767.) / 32767.;
   d = fabs(vi[j] - gh);
   e = fabs(vq[j] - hg);
   xd = abs(d - dd);
   ye = abs(e - ee);
   if( xd > 0.5){
   xyd = d;}
   if( ye > 0.5){
   xye = e;}
   if( d > 1.0 ){
   vi[j] = xyd + vi[j];}
   if( e > 1.0 ){
   vq[j] = xye + vq[j];}
   gh = vi[j];
   hg = vq[j];
   dd = d;
   ee = e;
   xu = A1 * vi[j] + B1 * vq[j];
   yu = C1 * vq[j] + D1 * vi[j];
   fdata[j] = (i + j) / 300.;
   vi[j] = (cos(rr) * xu - sin(rr) * yu - xerr) + 2400;
   vq[j] = (sin(rr) * xu + cos(rr) * yu - yerr) - 1800;
   if(xerr == 0. | yerr == 0.)
   {
      xerr = vi[0];
      yerr = vq[0];
      vi[0] = 0.000001;
      vq[0] = 0.000001;
   }
```

```
      vph[j] = atan2(vq[j], vi[j])*180./3.1415926;
      if(-750. < vi[j] & vi[j] < 750. | -750. < vq[j] & vq[j] < 750.)
      {
         vph[j] = 45.;
      }
    }
  i = j * k;
  if(y[0] == 121 | y[0] == 89)
  {
   for(j = 0; j < l; j++)
   {
     f = atan2(vq[j], vi[j]) * 180. / 3.1415927;
     fprintf(dstream," %f   %f  , %f\n", vi[j], vq[j], f);
   }
  }
  if(yy[0] == 121 | yy[0] == 89)
  {
    ptime(vi, vq, vph, fdata, l);
    impedanc(vi, vq, l);
  }
  fclose(handle);
 }
 fclose(stream);
 fclose(dstream);
}

void ptime(float *vi, float *vq, float *vph, float *fdata, int l)
{
   InitSEGraphics("c:\\turboc");
   SortDataX(fdata, vi+96, l-97, 1);
   SortDataX(fdata, vq+96, l-97, 1);
   SetCurrentWindow(7);
   SetAxesType(0, 0);
   SelectColor(4);
   ScalePlotArea(fdata[0], -8000., fdata[l-97], 8000.);
   SetXYIntercepts(fdata[0], 0.);
   DrawXAxis(1., 0);
   DrawYAxis(500., 0);
   LabelXAxis(2,0);
   LabelYAxis(2,0);
   BorderCurrentWindow(16);
   strcpy(xtitle,"      TIME (sec.)     ");
   TitleXAxis(xtitle);
   TitleWindow("  Eddy-Current Impedance Waveform  ");
```

```
    strcpy(xtitle," Resistance ");
    TitleYAxis(xtitle);
    LinePlotData(fdata+96, vi+96, l-97, 4, 0);
    SetCurrentWindow(9);
    SetAxesType(0,0);
    SelectColor(4);
    ScalePlotArea(fdata[0], -8000., fdata[l-97], 8000.);
    SetXYIntercepts(fdata[0], 0.);
    DrawXAxis(1., 0);
    DrawYAxis(500.0, 0);
    LabelXAxis(2,0);
    LabelYAxis(2,0);
    BorderCurrentWindow(16);
    strcpy(xtitle,"     TIME (sec.)     ");
    TitleXAxis(xtitle);
    TitleWindow(" Eddy-Current Impedance Waveform  ");
    strcpy(xtitle," Reactance  ");
    TitleYAxis(xtitle);
    LinePlotData(fdata+96, vq+96, l-97, 4, 0);
    SetCurrentWindow(8);
    SetAxesType(0,0);
    SelectColor(4);
    ScalePlotArea(fdata[0], -300., fdata[l-97], 300);
    SetXYIntercepts(fdata[0], 0.);
    DrawXAxis(1., 0);
    DrawYAxis(100.0, 0);
    LabelXAxis(1,0);
    LabelYAxis(1,0);
    BorderCurrentWindow(16);
    strcpy(xtitle,"  TIME(sec.)  ");
    TitleXAxis(xtitle);
    TitleWindow(" Eddy-Current Phase Angle ");
    strcpy(xtitle," Phase Angle ");
    TitleYAxis(xtitle);
    LinePlotData(fdata+96, vph+96, l-97, 4, 0);
}

void impedanc(float *vi, float *vq, int l)
{
    int sy;
    SetCurrentWindow(10);
    SetAxesType(0,0);
    SelectColor(4);
    ScalePlotArea(-8000., -8000., 8000, 8000.);
    SetXYIntercepts(0., 0.);
    DrawXAxis(500., 0);
    DrawYAxis(500., 0);
    LabelXAxis(4, 0);
    LabelYAxis(4, 0);
    BorderCurrentWindow(16);
    strcpy(xtitle," Resistance ");
    TitleXAxis(xtitle);
    TitleWindow("  Eddy-Current Impedance Plane  ");
    strcpy(xtitle," Reactance ");
    TitleYAxis(xtitle);
    LinePlotData(vi+96, vq+96, l-97, 4, 0);
    sy = getch();
    if(sy == 121 | sy == 89)
    ScreenDump(3, 0, 3, 3, 2, 0, 0, &err);
    {
      PlotterOn();
    }
    ClearWindow();
    CloseSEGraphics();
}
```